Geoneutrinos and heat production in the Earth: constraints and implications

Geophysics tells us where we are at today

Geochemistry tells us how we got there…

***Geochemistry collaborator*:**
- Ricardo Arevalo : University of Maryland

***Geoneutrino collaborators*:**
- John Learned : University of Hawaii
- Steve Dye: Hawaii Pacific University

UNIVERSITY OF MARYLAND 1856

5 Big Questions:

- What is the Planetary K/U ratio?

planetary volatility curve

- Radiogenic contribution to heat flow?

secular cooling

- Distribution of reservoirs in mantle?

whole vs layered convection

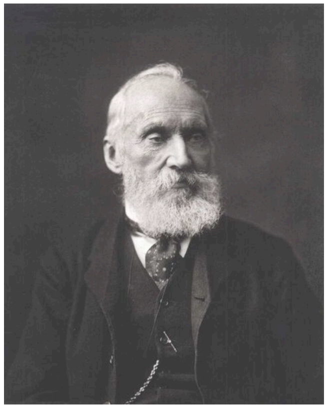
- Radiogenic elements in the core??

Earth energy budget

- Nature of the Core-Mantle Boundary?

hidden reservoirs

AGE OF THE EARTH
thermal evolution



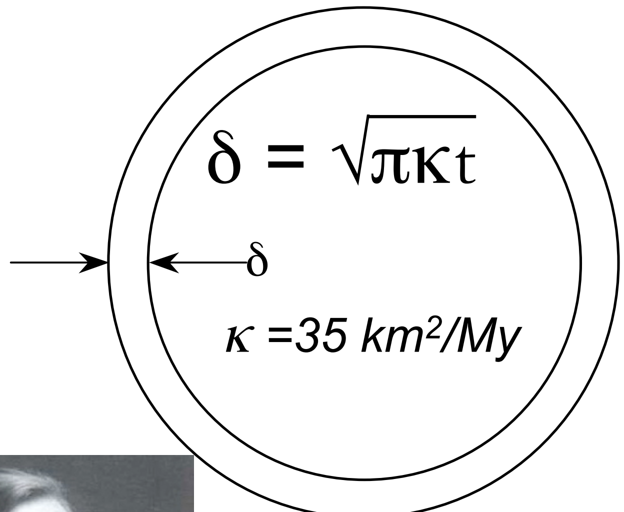
Lord Kelvin

1862

Conductive cooling of a **solid** planet

Age of Earth ~100 My

Heat loss depends on thermal boundary layer thickness δ



John Perry

1895

Conductive cooling of a planet with a **convecting** interior

Age of Earth ~1 Gy

radioactivity

Ernest Rutherford

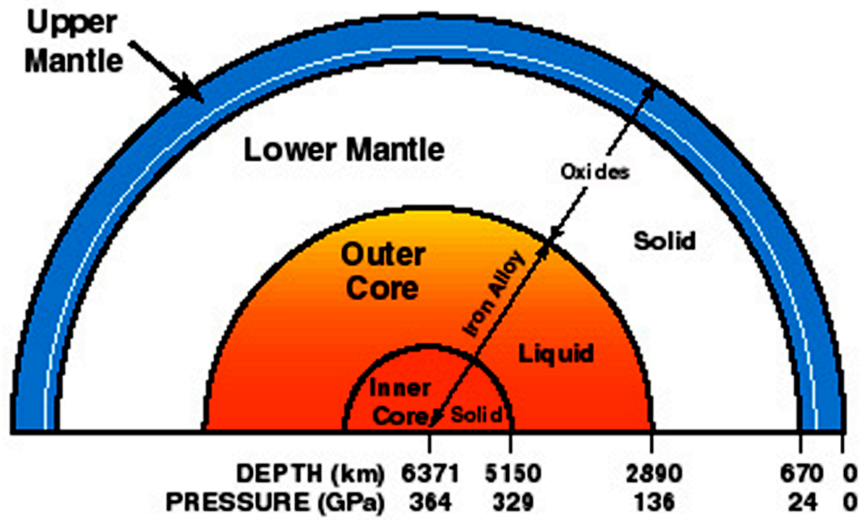
1904

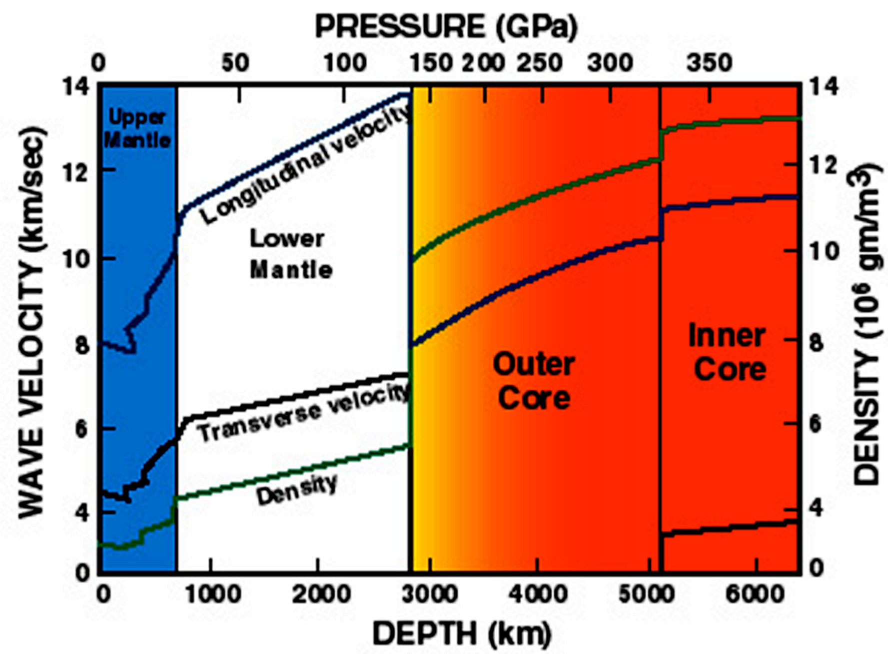
"… Kelvin had limited the age of the earth provided that no new source of heat was discovered. … what we are considering tonight, **radium**!"

Rutherford fondly recalled, "Behold! the old boy beamed upon me." (*Kelvin was in the audience*)

In 1897, Earth's 1st order structure -- silicate shell surrounding metal core

Emil Johann Wiechert
1861-1928





"Standard" Planetary Model

- Chondrites, primitive meteorites, are key
- So too, the composition of the solar photosphere
- Refractory elements (RE) in chondritic proportions
- Absolute abundances of RE – model dependent
- **Mg, Fe & Si** are non-refractory elements
- Chemical gradient in solar system →
- Non-refractory elements – model dependent
- U & Th are RE, whereas K is moderately volatile

Meteorites

Achondrite, Ca-poor, Diogenite

Mantle-crust pieces (?)

Allende

chondrites

undifferentiated planets (?)

Carbonaceous chondrite (CV3)

Pallasite: olivine and iron mixtures (CMB?)

Irons: pieces of core

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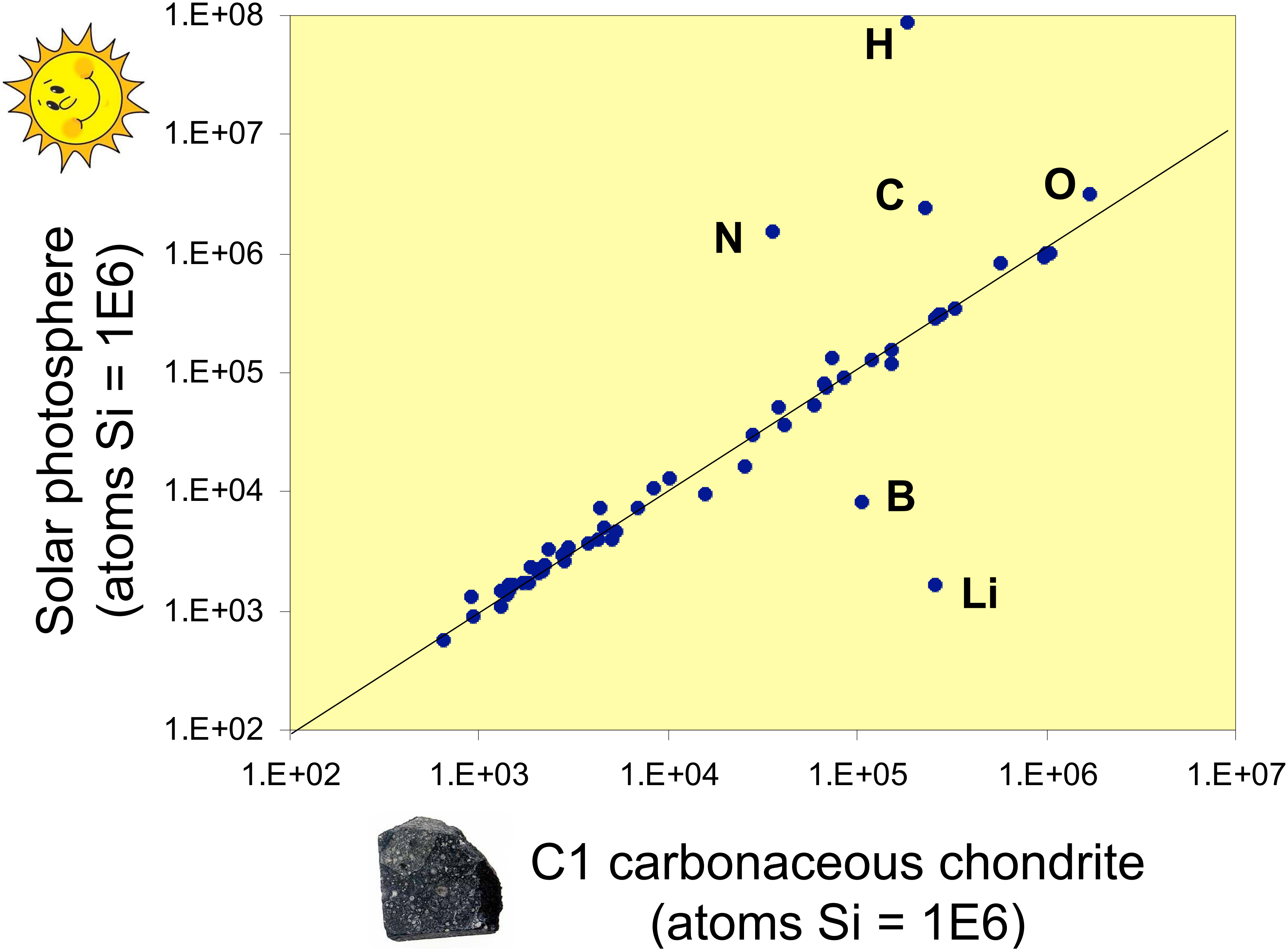

Solar photosphere
(atoms Si = 1E6)
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
H
C
O
N
B
Li
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
C1 carbonaceous chondrite
(atoms Si = 1E6)

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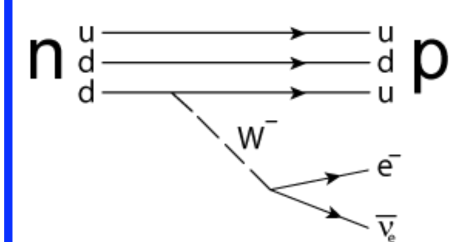
Detecting Geoneutrino in the Earth

Nature **436**, 499-503 (28 July 2005)

β⁻ decay



Detecting Electron Antineutrinos from inverse beta -decay

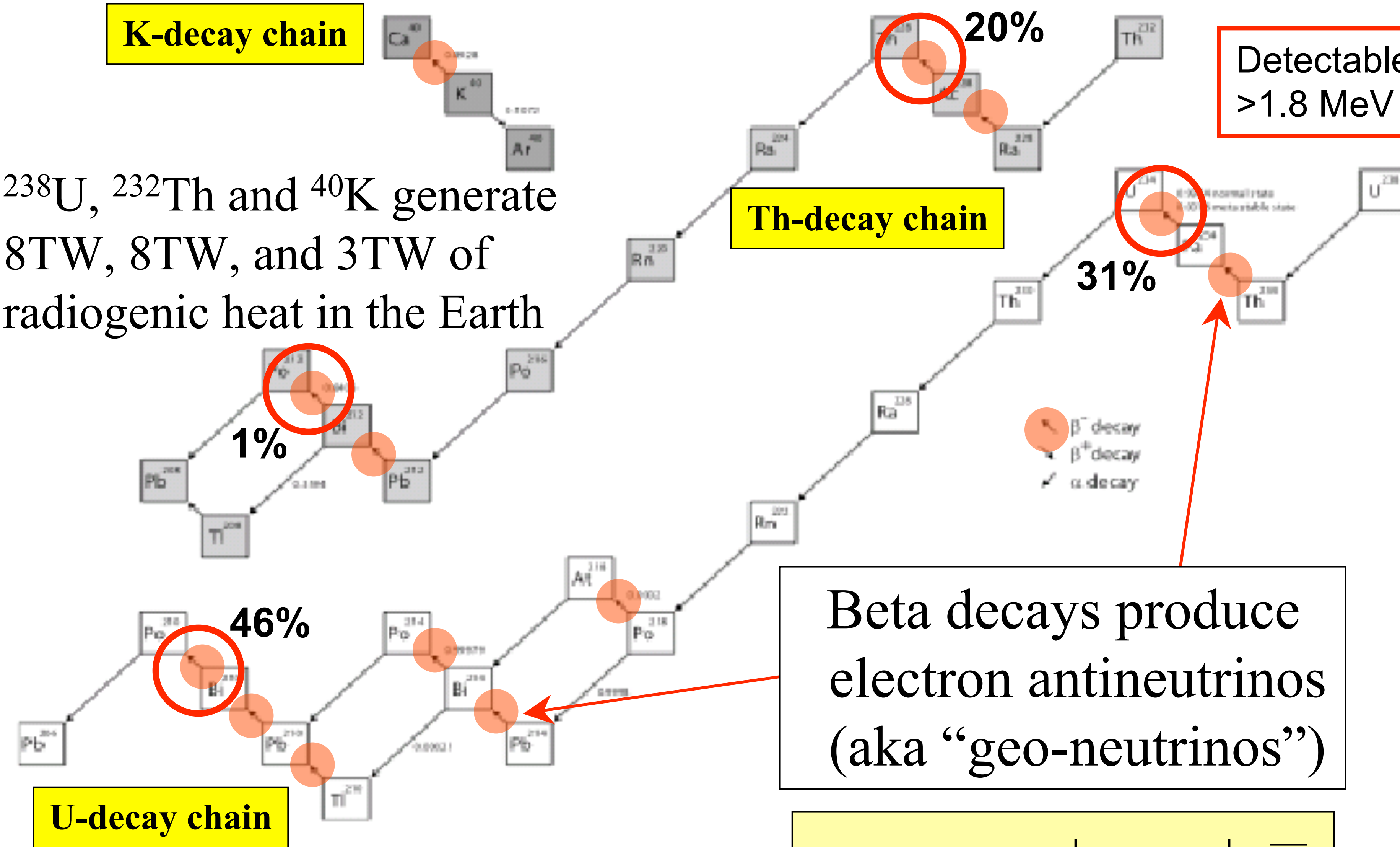
$$\bar{\nu}_e + p \rightarrow n + e^+$$

2 flashes close in space and time
Rejects most backgrounds

Radiogenic heat & “geo-neutrino”

^{238}U, ^{232}Th and ^{40}K generate 8TW, 8TW, and 3TW of radiogenic heat in the Earth

Detectable
>1.8 MeV



Beta decays produce electron antineutrinos (aka “geo-neutrinos”)

$$n \longrightarrow p + e^- + \overline{\nu}_e$$

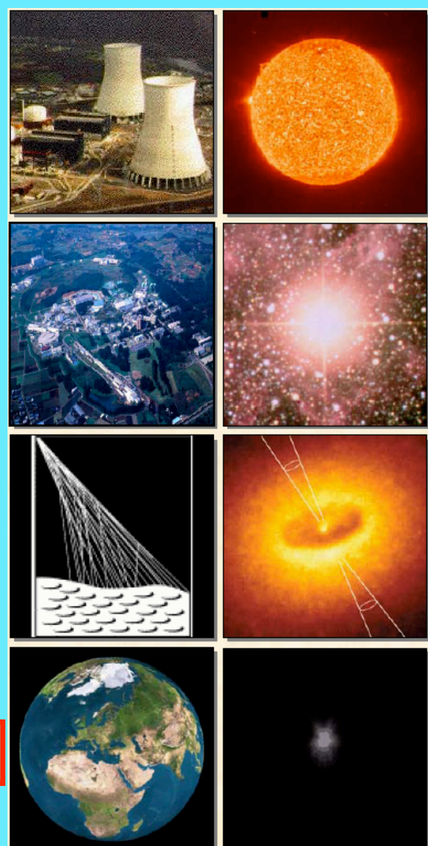
Neutrino Sources and Flux

Nuclear Reactors

Particle Accelerators

Cosmic Rays

Natural Radioactivity



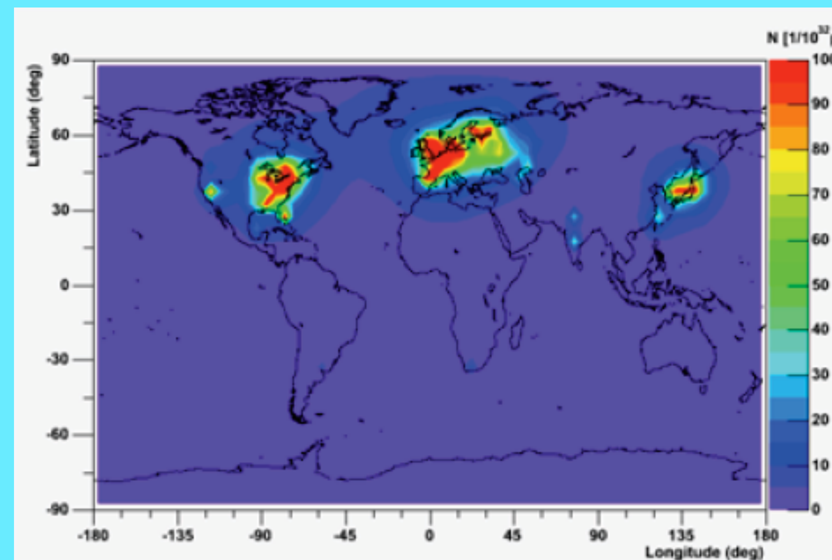
All Stars (Sun)

Supernova

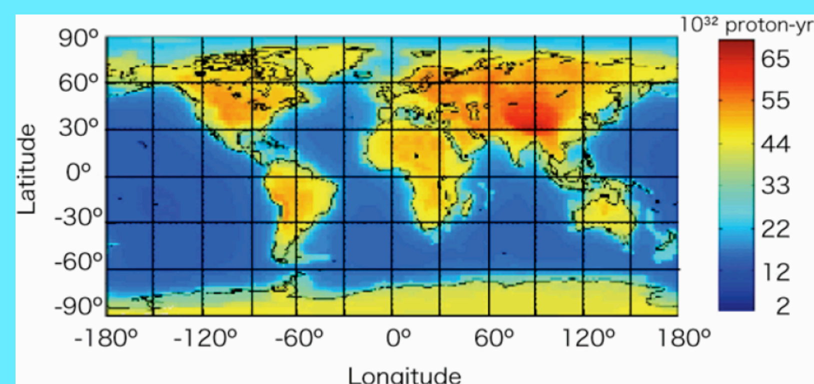
Black Holes/Quasars

Big Bang

Nuclear Reactor Flux



Predicted Geoneutrino Flux



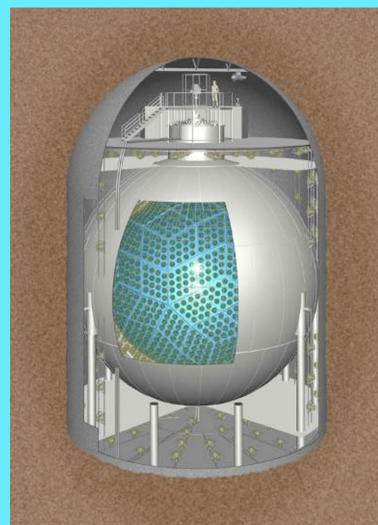
Current Neutrino Detectors

IceCube

ν Source: Galactic Nuclei

Detector Type: Cherenkov

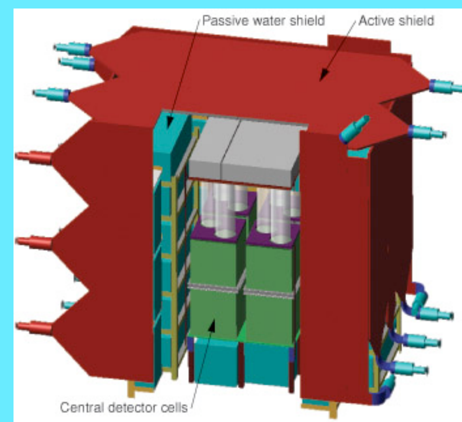
KAMLAND



ν Source: Geo and Nuclear

Detector Type: Scintillation

Bernstein Cube



ν Source: Nuclear

Detector Type: Scintillation

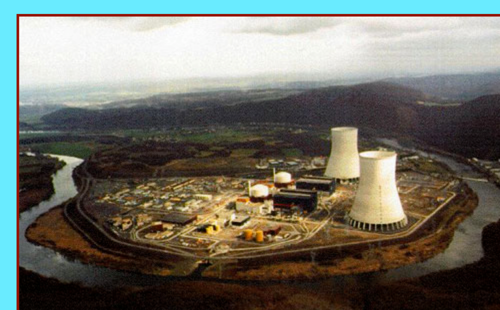
ANITA

ν Source: Galactic Nuclei

Detector Type: Cherenkov

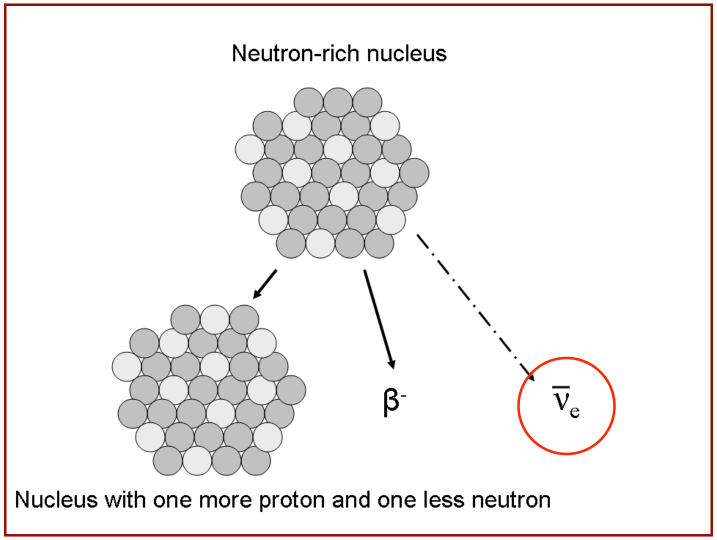
typical flux
$6{*}10^{6}\ \bar{\nu}\ cm^{2}\ s^{-1}$

typical flux
$2{*}10^{20}\ \bar{\nu}\ s^{-1}$



MeV-Scale Electron Anti-Neutrino Detection

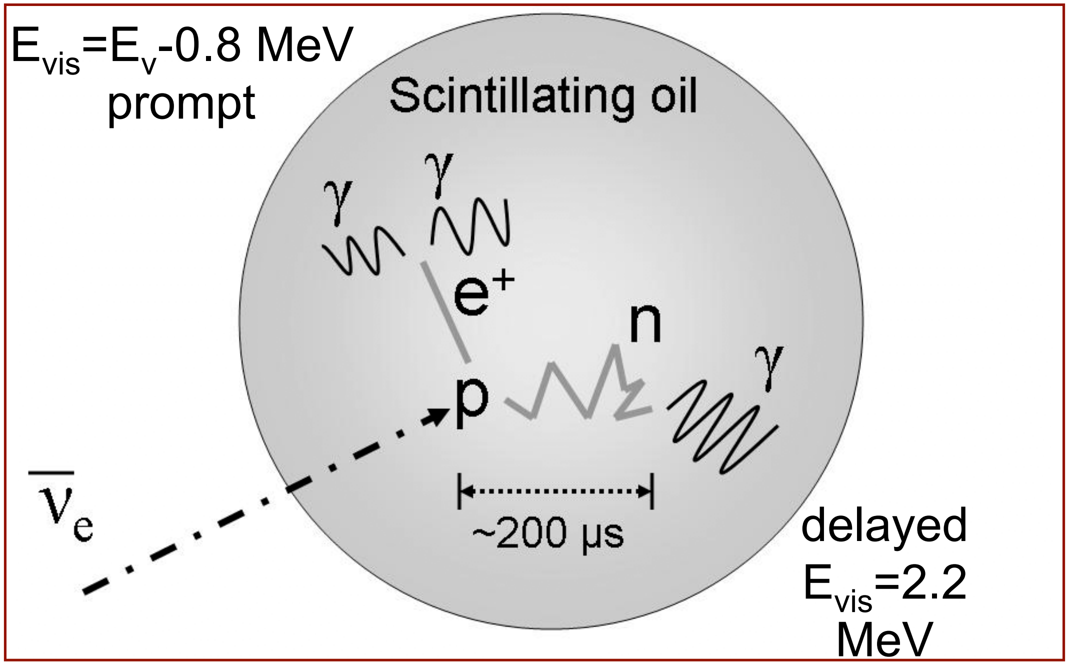
Production in reactors and natural decays



Reines & Cowan

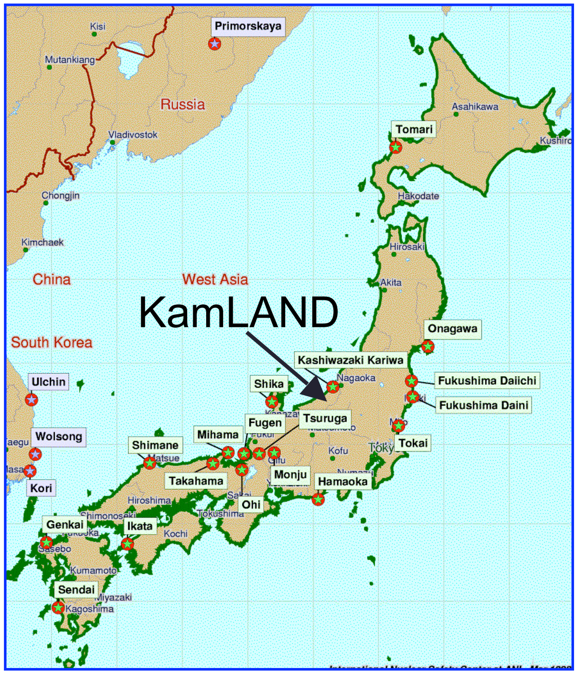
Key: **2 flashes, close in space and time,**
2nd of known energy, **eliminate background**

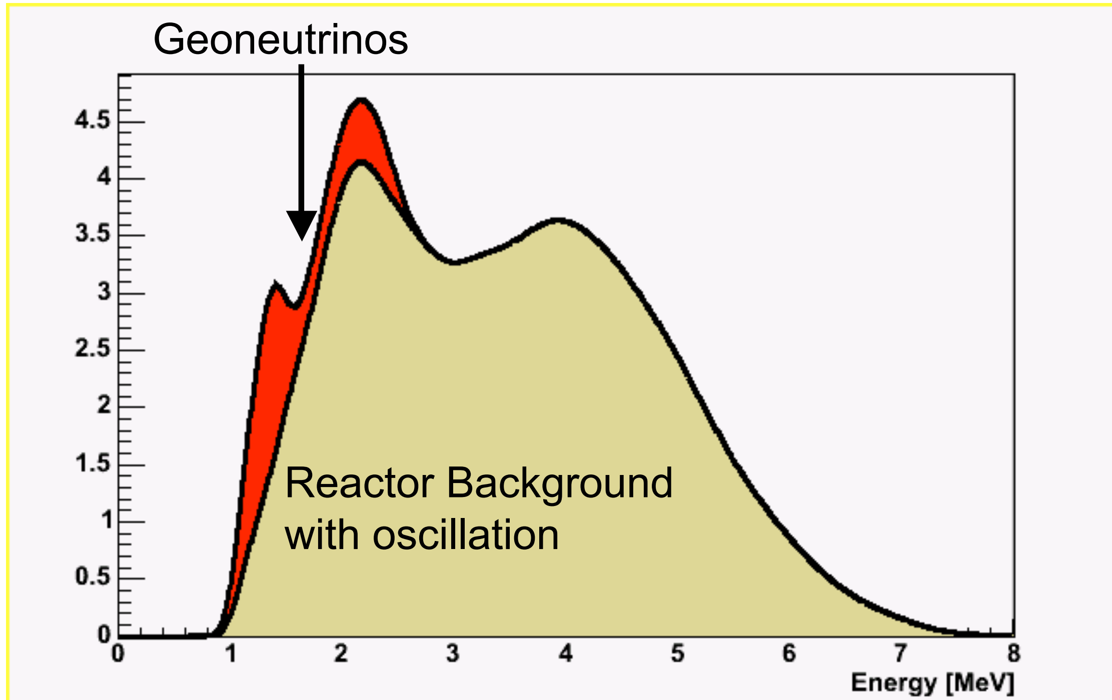
Detection



- Standard inverse β-decay coincidence
- $E_\nu > 1.8$ MeV
- Rate and spectrum - no direction

Reactor Background





- KamLAND was designed to measure reactor antineutrinos.
- Reactor antineutrinos are the most significant background.

naturenews

Published online 15 May 2008 | Nature | doi:10.1038/news.2008.822

News

Are there nuclear reactors at Earth's core?

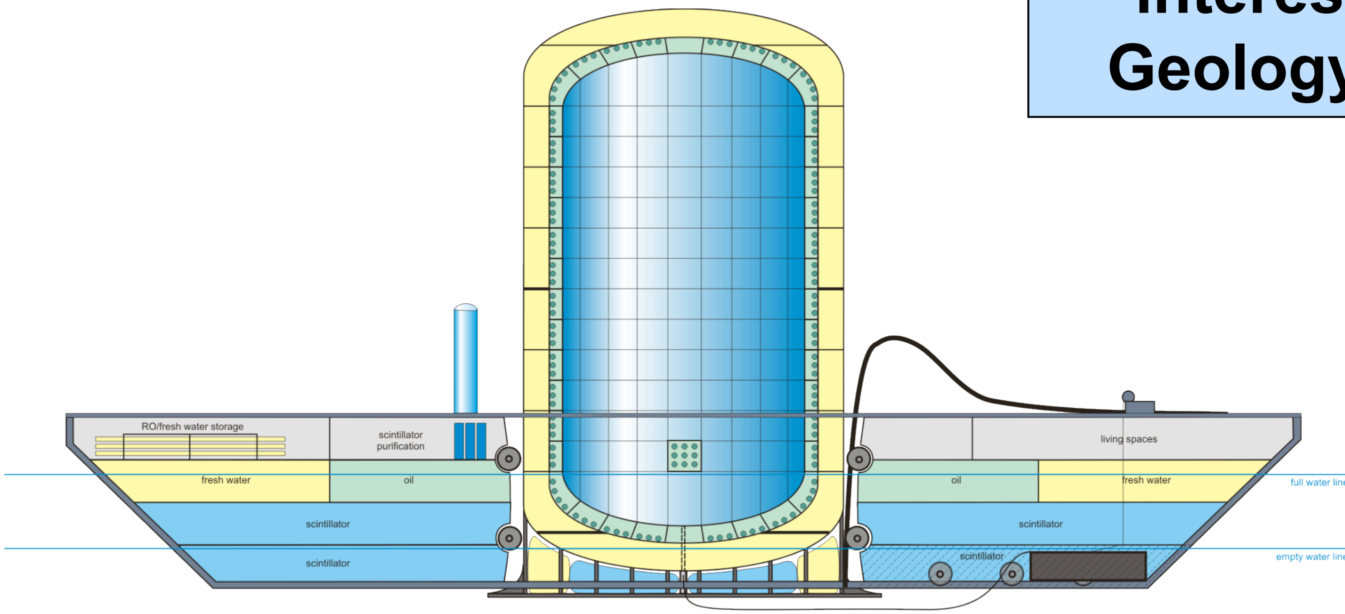
Fission reactors may have been burning for billions of years.

Published May 2008

Could this be home to buried nuclear infernos?

Hanohano

An experiment with joint interests in Physics, Geology, and Security

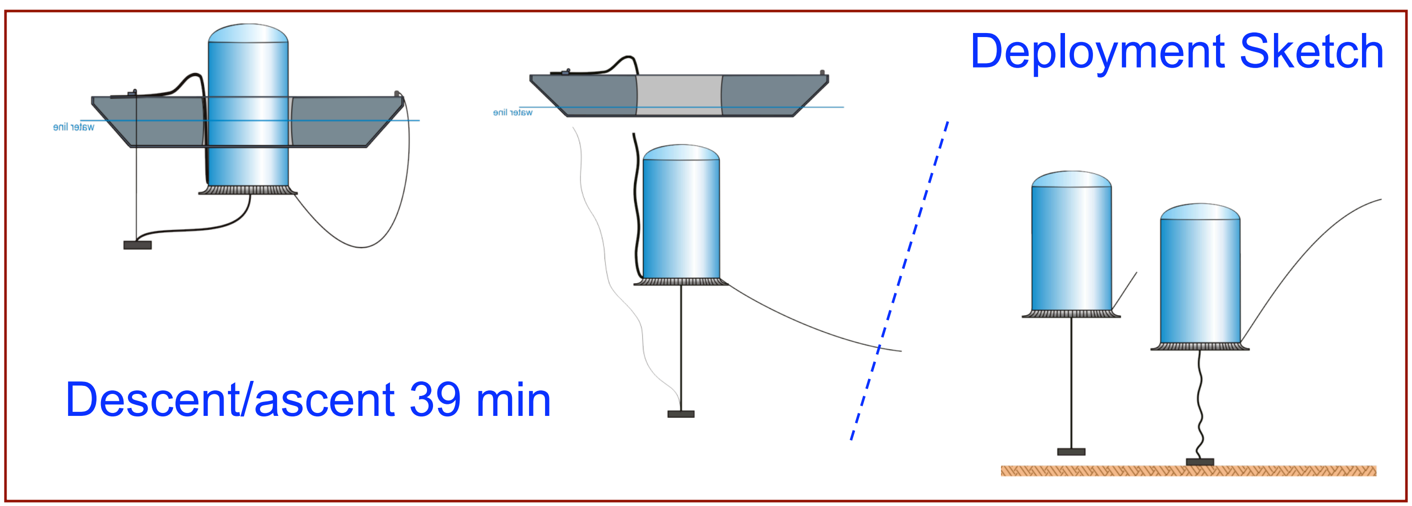


- multiple deployments
- deep water cosmic shield
- control-able L/E detection

Deep Ocean

$\overline{\nu}_e$

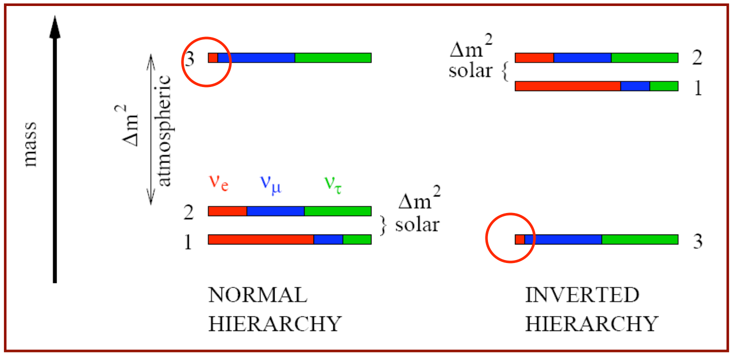
Observatory



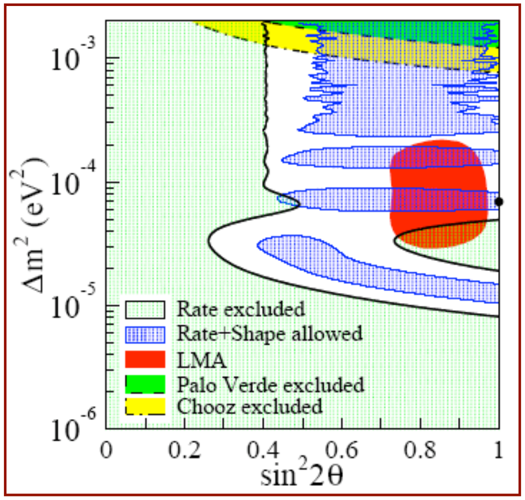
Neutrino Oscillation Physics with Hanohano

- **Precision measurement of mixing parameters needed**
  (4 of 5 in Hanohano)
- **World effort to determine θ_{13} (= θ_{31})**
  (Hanohano, unique method)
- **Determination of mass hierarchy**
  (Hanohano novel method, late '06)
- **Neutrino properties relate to origin of matter, formation of heavy elements, and may be key to unified theory.**

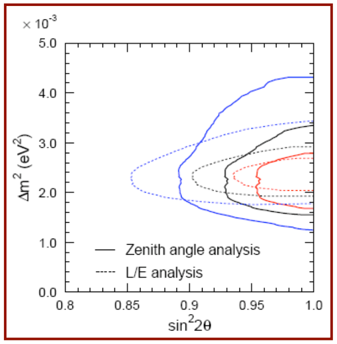
MNSP Mixing Matrix



2 mass diffs, 3 angles, 1 CP phase



Solar, KamLAND



Atmospheric, SuperK

3-ν Mixing: Reactor Neutrinos

$$P_{ee}=1-\{\cos^4(\theta_{13})\sin^2(2\theta_{12})[1-\cos(\Delta m^2_{12}L/2E)]$$
$$+\cos^2(\theta_{12})\sin^2(2\theta_{13})[1-\cos(\Delta m^2_{13}L/2E)]$$
$$+\sin^2(\theta_{12})\sin^2(2\theta_{13})[1-\cos(\Delta m^2_{23}L/2E)]\}/2$$

wavelength close, 3%

mixing angles

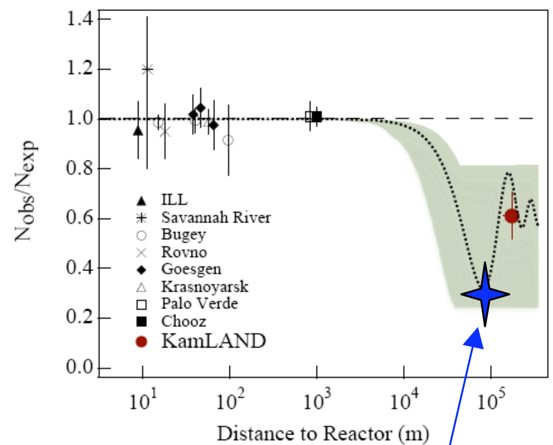
mass diffs

- Survival probability: 3 oscillating terms each cycling in L/E space (~t) with own "periodicity" ($\Delta m^2 \sim \omega$)
  - Amplitude ratios ~13.5 : 2.5 : 1.0
  - Oscillation lengths ~110 km (Δm^2_{12}) and ~4 km ($\Delta m^2_{13} \sim \Delta m^2_{23}$) at reactor peak ~3.5 MeV
- ½-cycle measurements can yield
  - Mixing angles, mass-squared differences
- Multi-cycle measurements can yield
  - Mixing angles, precise mass-squared differences
  - Mass hierarchy
  - **Less sensitivity to systematic errors**

½-cycle θ_{12} (=θ_{21}) measurement

with Hanohano

- Reactor experiment- $\bar{\nu}_e$ point source
- $P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2(2\theta_{12})\sin^2(\Delta m^2_{21} L/4E)$
- 60 GW·kt·y exposure at 50-70 km
  - ~4% systematic error from near detector
  - $\sin^2(\theta_{12})$ measured with ~2% uncertainty

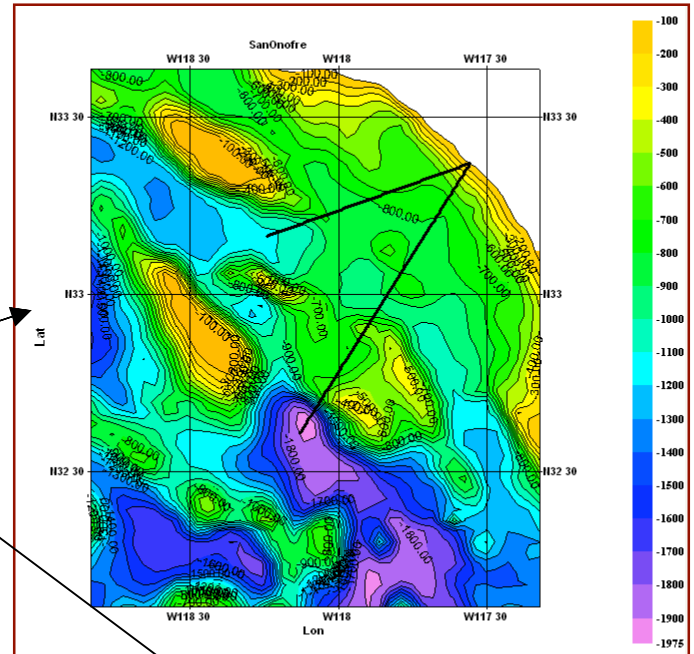


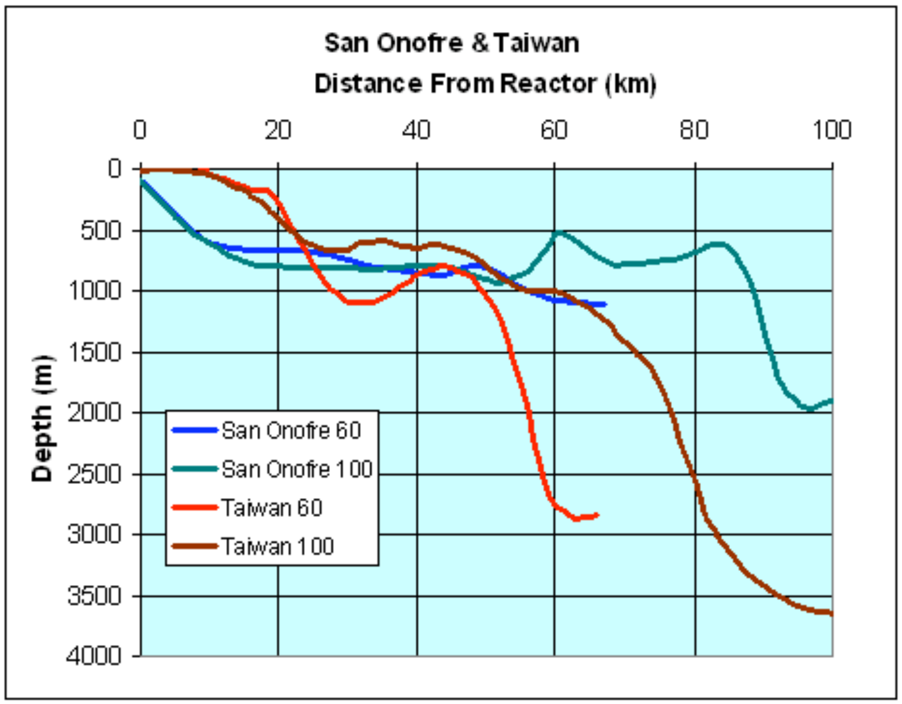
oscillation maximum at ~ 50-60 km

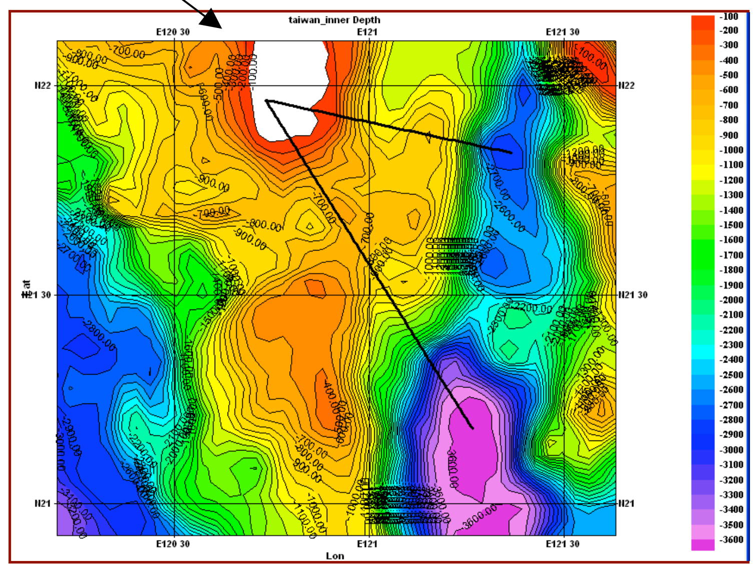
Bandyopadhyay et al., *Phys. Rev.* **D67** (2003) 113011.
Minakata et al., hep-ph/0407326
Bandyopadhyay et al., hep-ph/0410283

Candidate Off-shore Sites

San Onofre, California- ~6 GW_{th}
Maanshan, Taiwan- ~5 GW_{th}

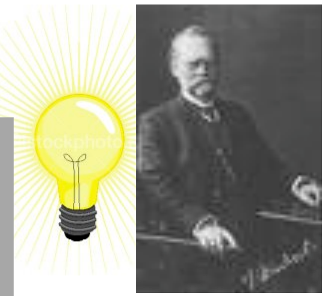






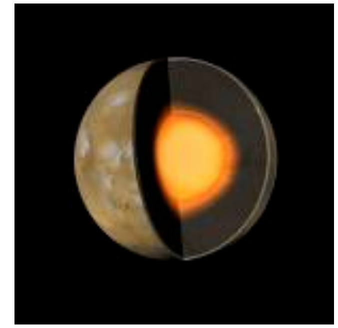
Time Line

1897



Emil Wiechert

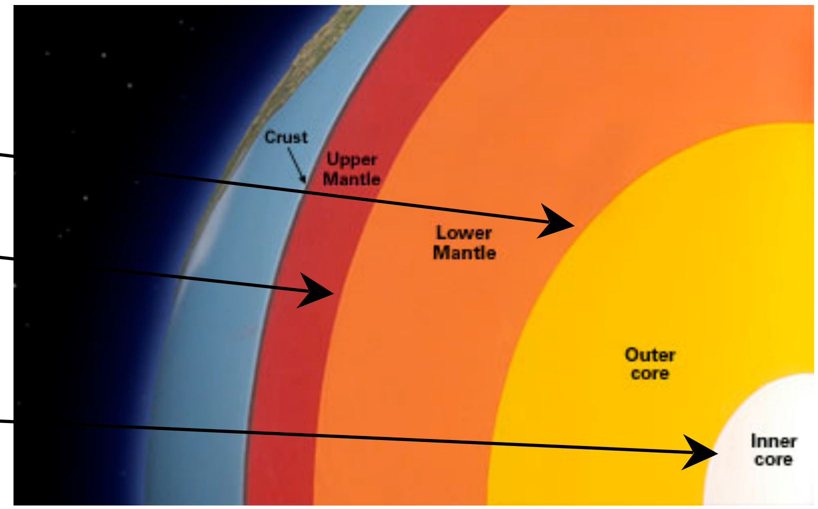
1st order Structure of Earth
Rock surrounding metal



1915 — CORE-MANTLE

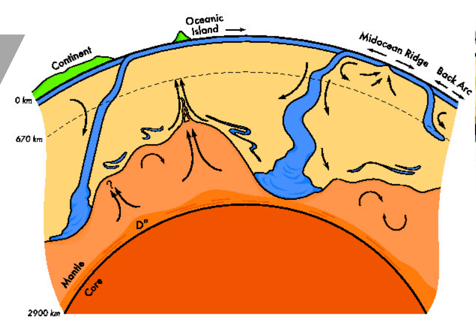
1925 — UPPER-LOWER MANTLE

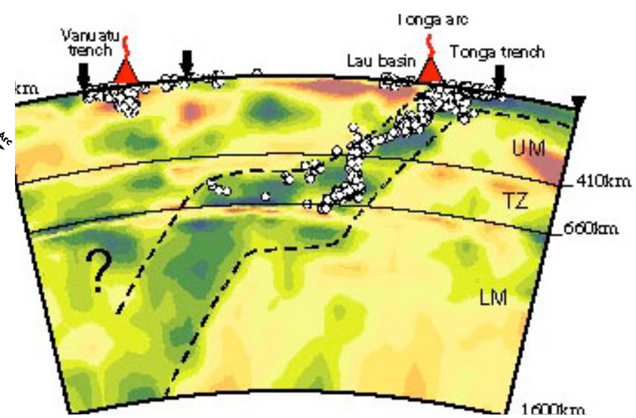
1935 — INNER-OUTER CORE

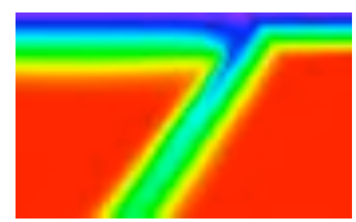


1970 — **PLATE TECTONICS**

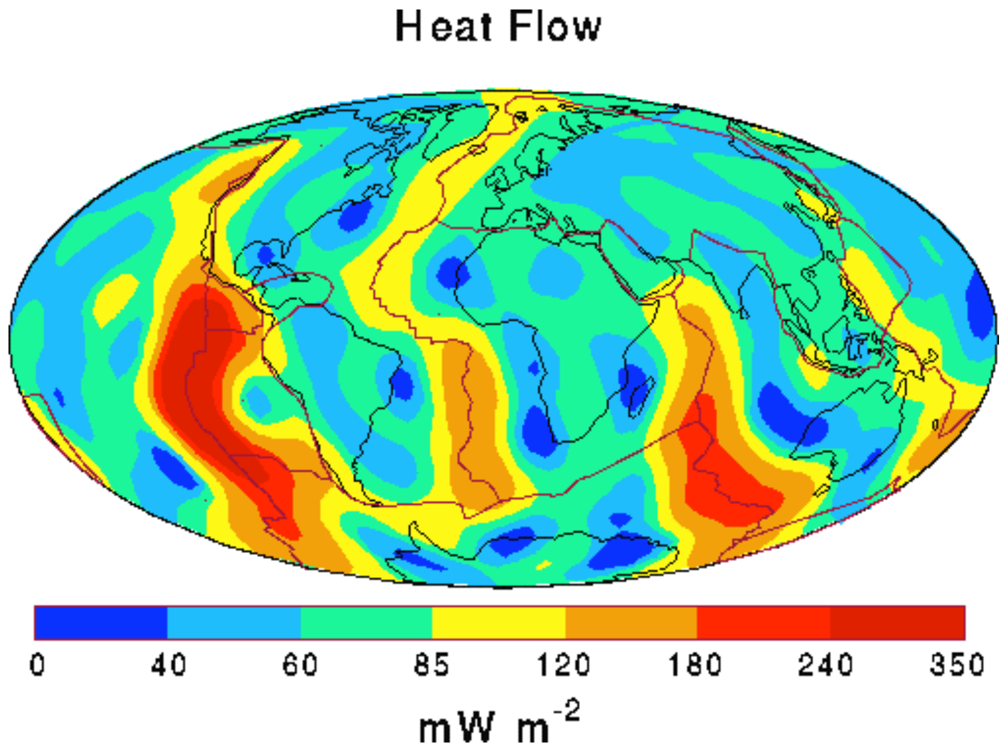
1995



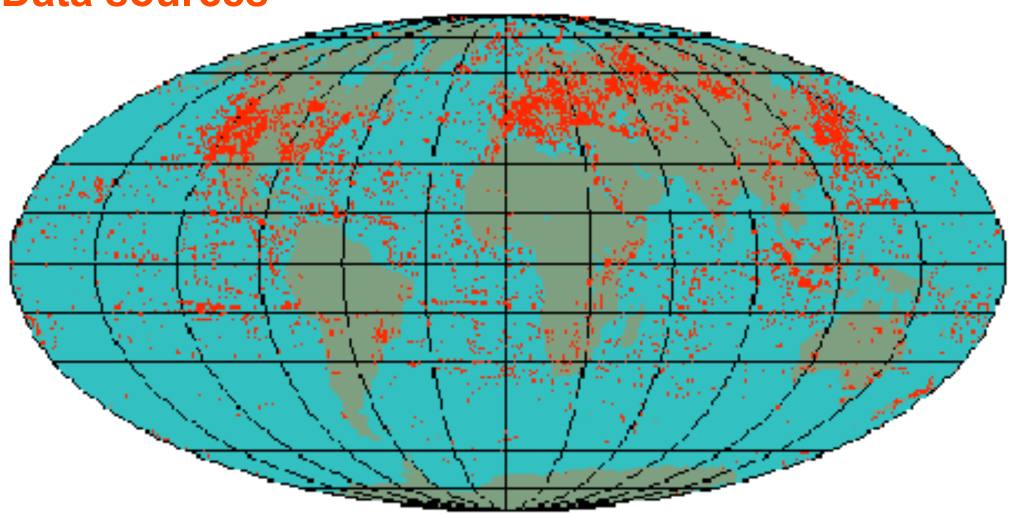




Earth's Total Surface Heat Flow



Data sources



- Conductive heat flow measured from bore-hole temperature gradient and conductivity

Total heat flow

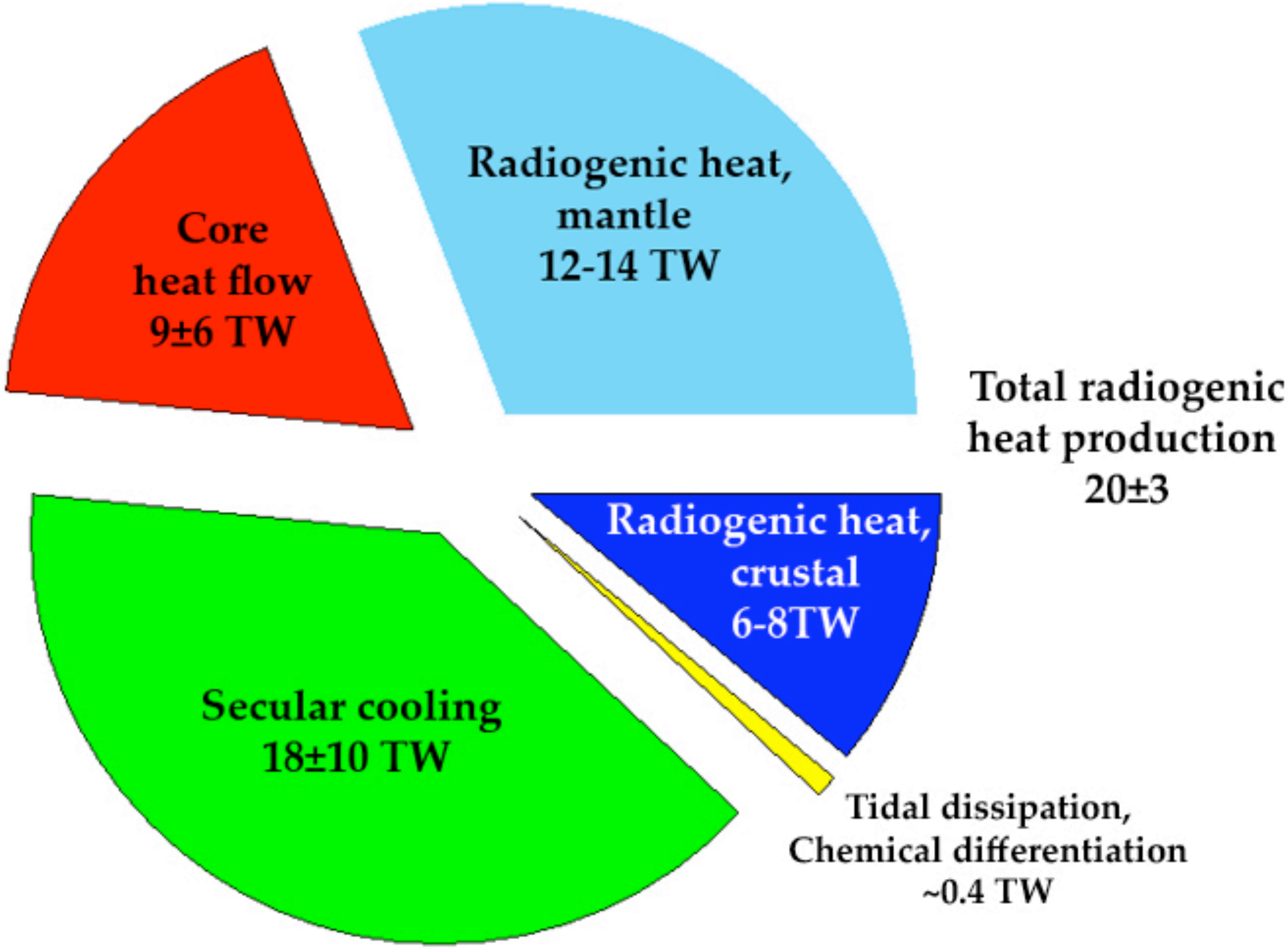
<u>Conventional view</u>

46±3 TW

<u>Challenged recently</u>

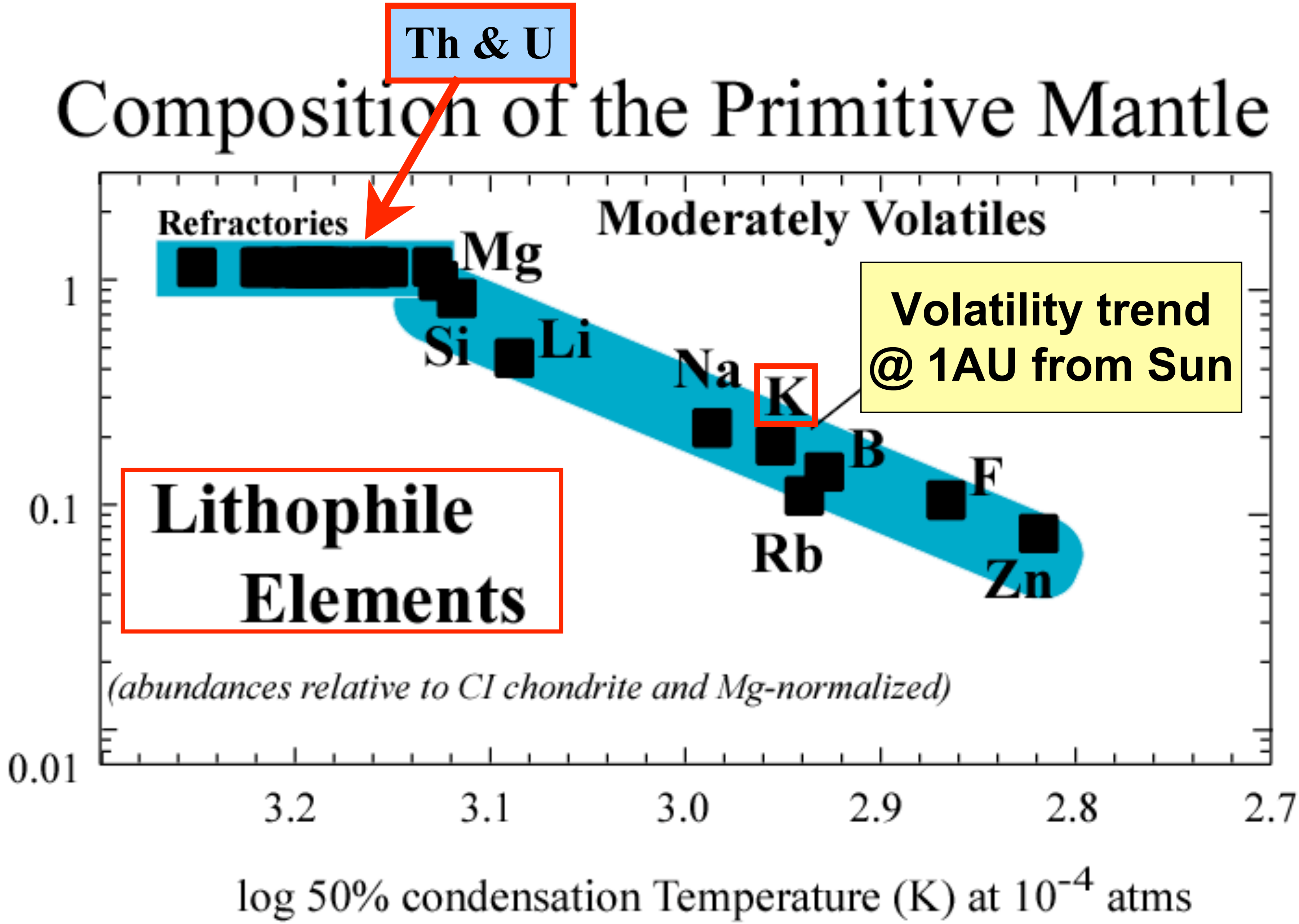
31±1 TW

Earth's surface heat flow (total 46 ±3)

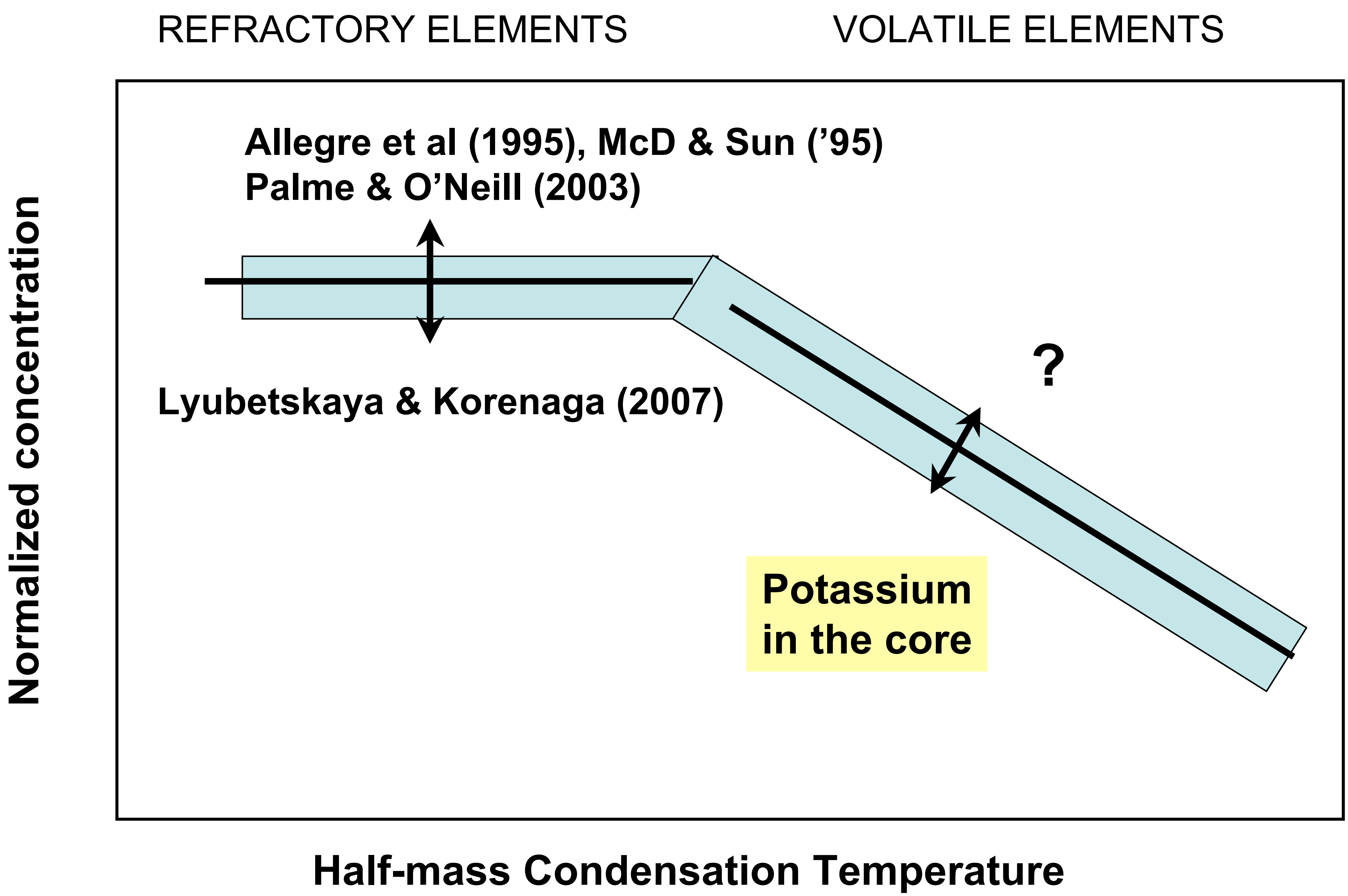


after Jaupart et a 2008 Treatise of Geophysics

Composition of the Primitive Mantle



Silicate Earth



sub-title: **What is the K/U Th/U ratios for the Earth and modern mantle?**

Implications and History

-- <u>implications</u>: K, Th and U are the radioactive elements that provide the sum of the internal radiogenic heat for the planet

-- <u>history</u>: Urey 1950s
Wasserburg 1960s
Jochum 1980s

First observations -- got it right at the 1-sigma level

Proceedings of the

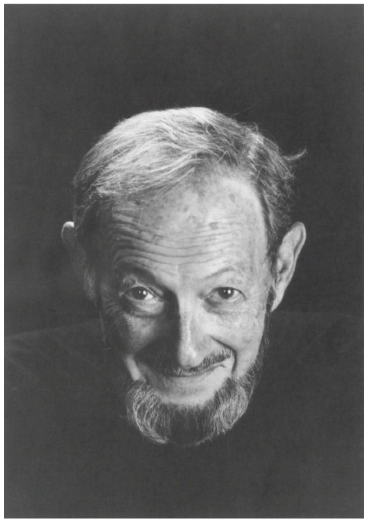
NATIONAL ACADEMY OF SCIENCES

Volume 42 · Number 12 · December 15, 1956

THE COSMIC ABUNDANCES OF POTASSIUM, URANIUM, AND THORIUM AND THE HEAT BALANCES OF THE EARTH, THE MOON, AND MARS

BY HAROLD C. UREY

ENRICO FERMI INSTITUTE FOR NUCLEAR STUDIES, UNIVERSITY OF CHICAGO, AND CLARENDON LABORATORY, OXFORD, ENGLAND (1956–1957)



SCIENCE 31 JANUARY 1964

G. J. WASSERBURG
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GORDON J. F. MACDONALD
Institute of Geophysics and Planetary Physics, University of California, Los Angeles

F. HOYLE
Cambridge University, Cambridge, England

WILLIAM A. FOWLER
California Institute of Technology

Accepted as the fundamental reference and set the bar at

$K/U = 10^4$
$Th/U = 3.5$ to 4.0

Relative Contributions of Uranium, Thorium, and Potassium to Heat Production in the Earth

Abstract. *Data from a wide variety of igneous rock types show that the ratio of potassium to uranium is approximately* 1×10^4. *This suggests that the value of* $K/U \approx 1 \times 10^4$ *is characteristic of terrestrial materials and is distinct from the value of* 8×10^4 *found in chondrites. In a model earth with* $K/U \approx 10^4$, *uranium and thorium are the dominant sources of radioactive heat at the present time. This will permit the average terrestrial concentrations of uranium and thorium to be 2 to 4.7 times higher than that observed in chondrites. The resulting models of the terrestrial heat production will be considerably different from those for chondritic heat production because of the longer half-life of* U^{238} *and* Th^{232} *compared with* K^{40}.

MORB (i.e., the Depleted Mantle ~ Upper Mantle)

$K/U \sim 10^4$ and

slightly sub-chondritic Th/U

DM & Continental Crust – complementary reservoirs

DM + Cc = BSE

ahh, but the assumptions and samples…

K, U and Th in mid-ocean ridge basalt glasses and heat production, K/U and K/Rb in the mantle

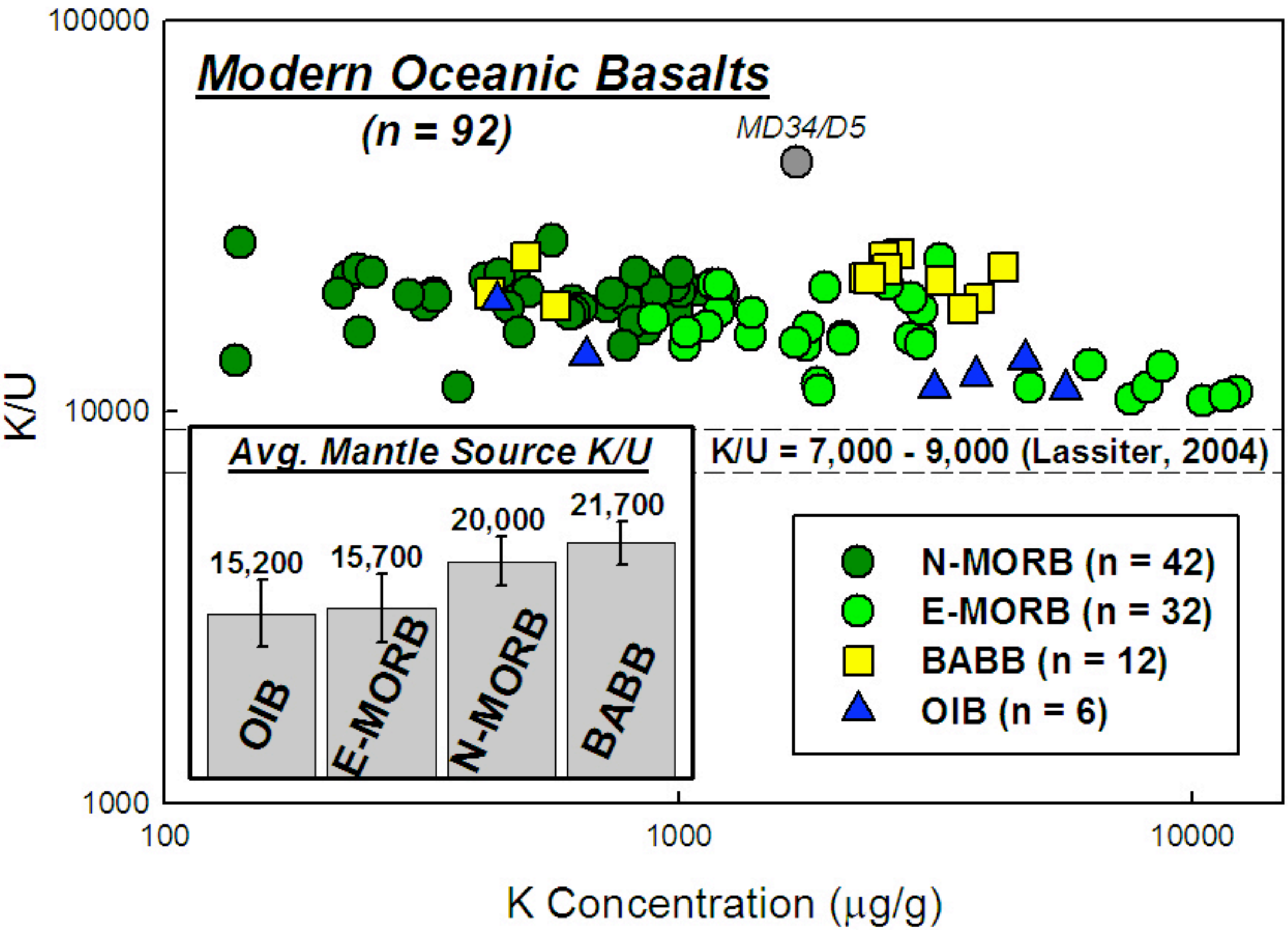
K. P. Jochum, A. W. Hofmann, E. Ito*, H. M. Seufert & W. M. White

Max-Planck-Institut für Chemie, Saarstrasse 23, 6500 Mainz, FRG

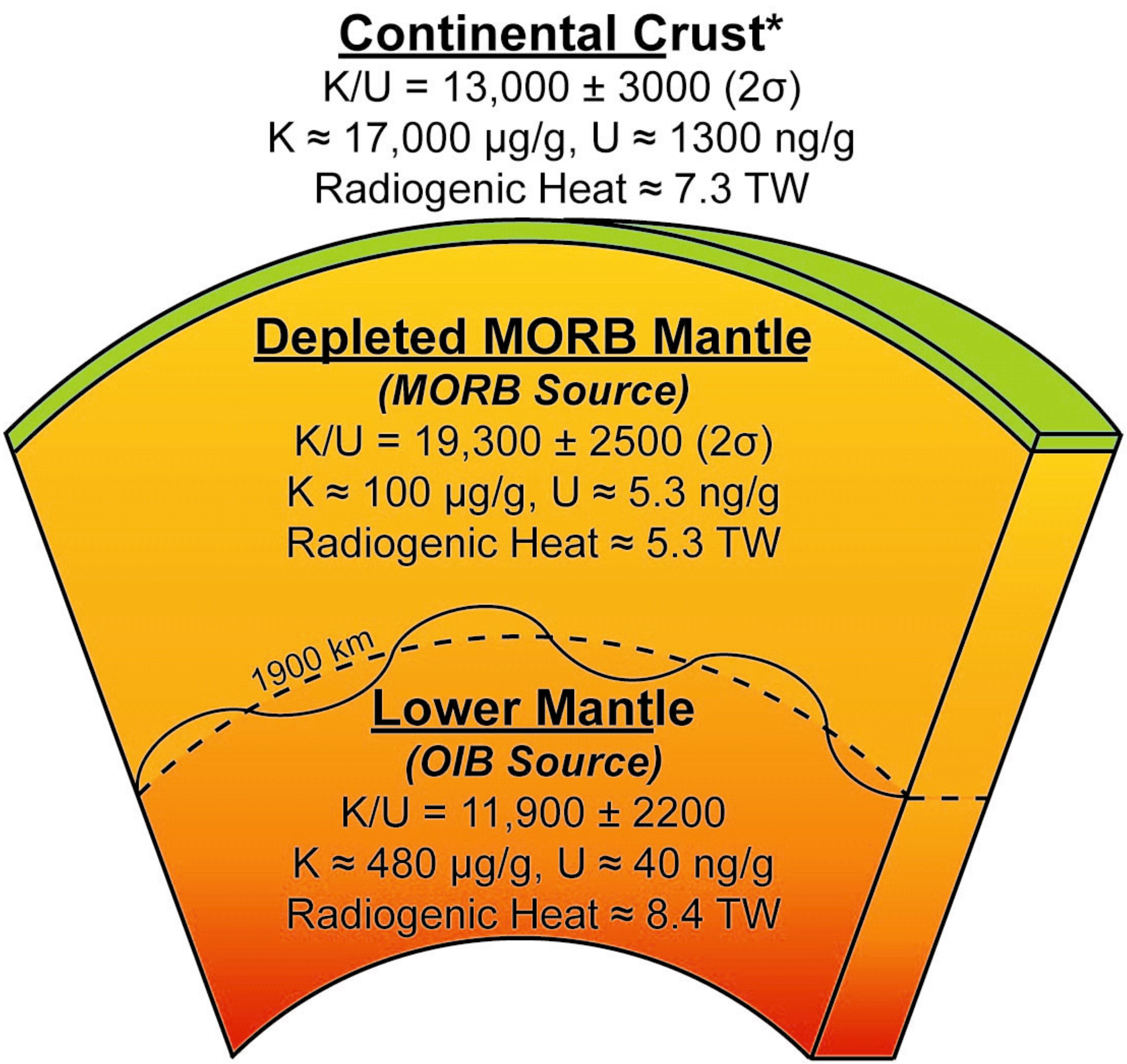
* Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington DC 20015, USA and Department of Geology, University of Minnesota, 310 Pillsbury Drive, S.E., Minneapolis, Minnesota 55455, USA

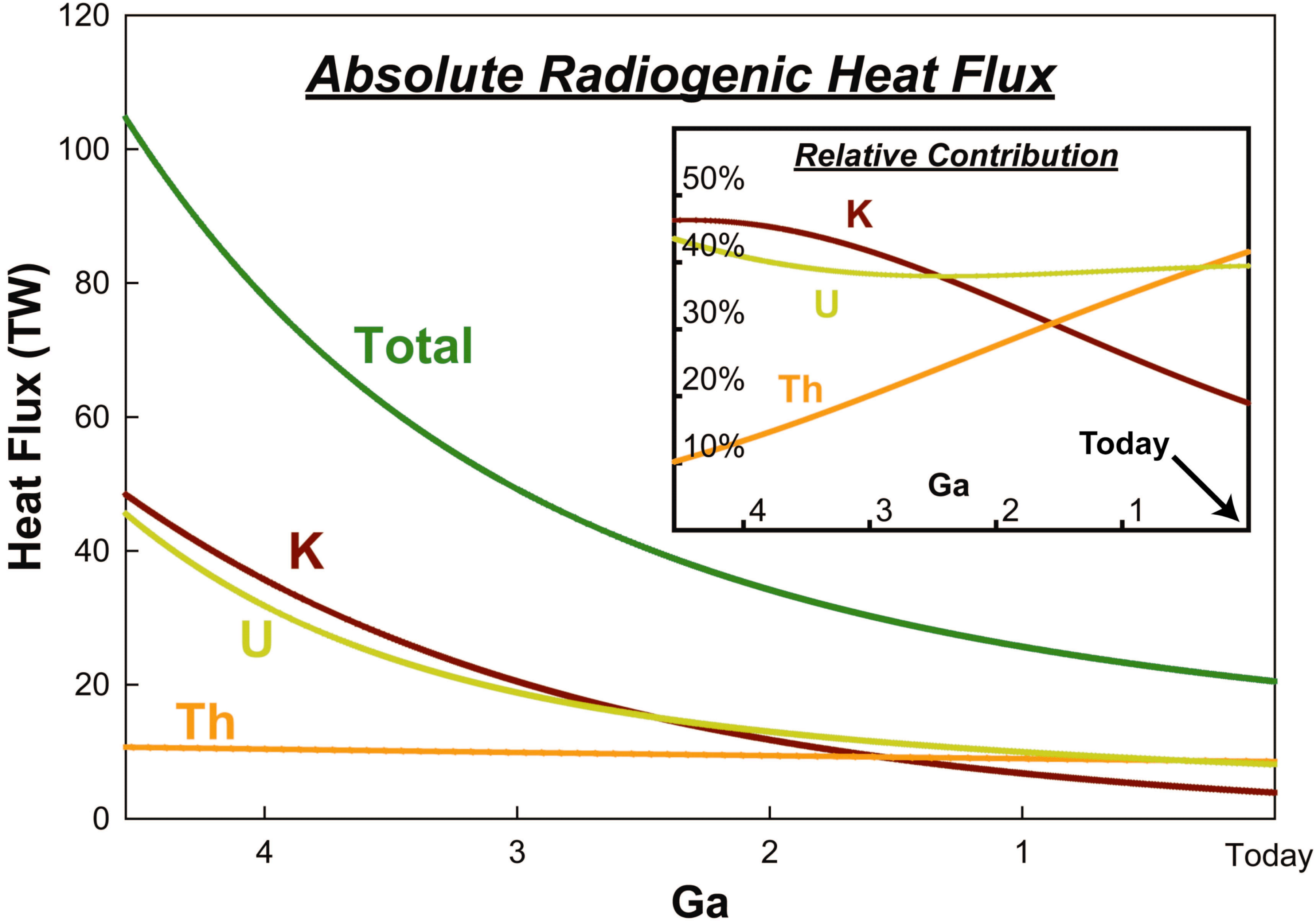
Analyses on fresh glass samples of mid-ocean ridge basalt yield a uniform ratio $K/U = 12{,}700 \pm 200$. In contrast, Th/U increases systematically with Th concentration. From these results we calculate an upper limit ($1.5\ pW\ kg^{-1}$) and a best estimate ($0.6\ pW\ kg^{-1}$) for the heat production in the depleted portion of the mantle. A new estimate is given for the terrestrial ratio of $K/Rb = 513$.

NATURE VOL. 306 1 DECEMBER 1983



Modern Oceanic Basalts
(n = 92)
MD34/D5
100000
10000
1000
K/U
100
1000
10000
K Concentration (µg/g)
K/U = 7,000 - 9,000 (Lassiter, 2004)
Avg. Mantle Source K/U
15,200
15,700
20,000
21,700
OIB
E-MORB
N-MORB
BABB
N-MORB (n = 42)
E-MORB (n = 32)
BABB (n = 12)
OIB (n = 6)


Continental Crust*
K/U = 13,000 ± 3000 (2σ)
K ≈ 17,000 µg/g, U ≈ 1300 ng/g
Radiogenic Heat ≈ 7.3 TW
Depleted MORB Mantle
(MORB Source)
K/U = 19,300 ± 2500 (2σ)
K ≈ 100 µg/g, U ≈ 5.3 ng/g
Radiogenic Heat ≈ 5.3 TW
1900 km
Lower Mantle
(OIB Source)
K/U = 11,900 ± 2200
K ≈ 480 µg/g, U ≈ 40 ng/g
Radiogenic Heat ≈ 8.4 TW

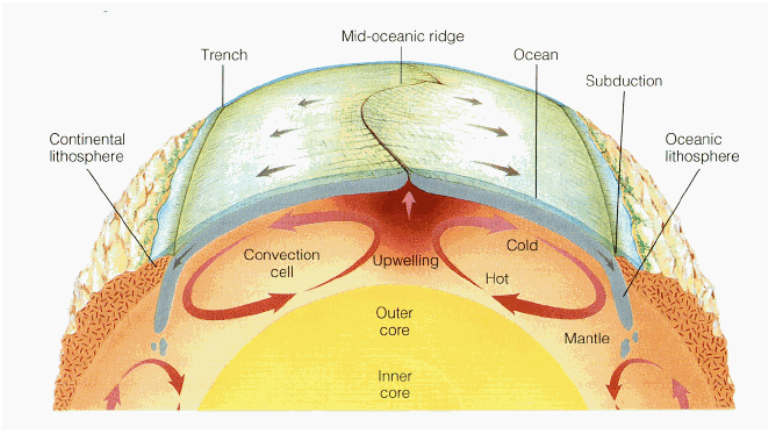


Absolute Radiogenic Heat Flux
Heat Flux (TW)
120
100
80
60
40
20
0
Total
K
U
Th
4
3
2
1
Today
Ga
Relative Contribution
50%
40%
30%
20%
10%
K
U
Th
Today
Ga
4
3
2
1

Urey Ratio and Mantle Convection Models

$$\text{Urey ratio} = \frac{\text{radioactive heat production}}{\text{heat loss}}$$

- Mantle convection models typically assume:
  mantle Urey ratio: 0.4 to 1.0, generally ~0.7
- Geochemical models predict:
  mantle Urey ratio 0.3 to 0.5



Discrepancy?

- Est. total heat flow, **46 or 31TW**
  est. radiogenic heat production **20TW or 31TW**
  give Urey ratio ~0.3 to ~1
- Where are the problems?
  - Mantle convection models?
  - Total heat flow estimates?
  - Estimates of radiogenic heat production rate?
- Geoneutrino measurements can constrain the planetary radiogenic heat production.

U and Th (and K) Distribution in the Earth

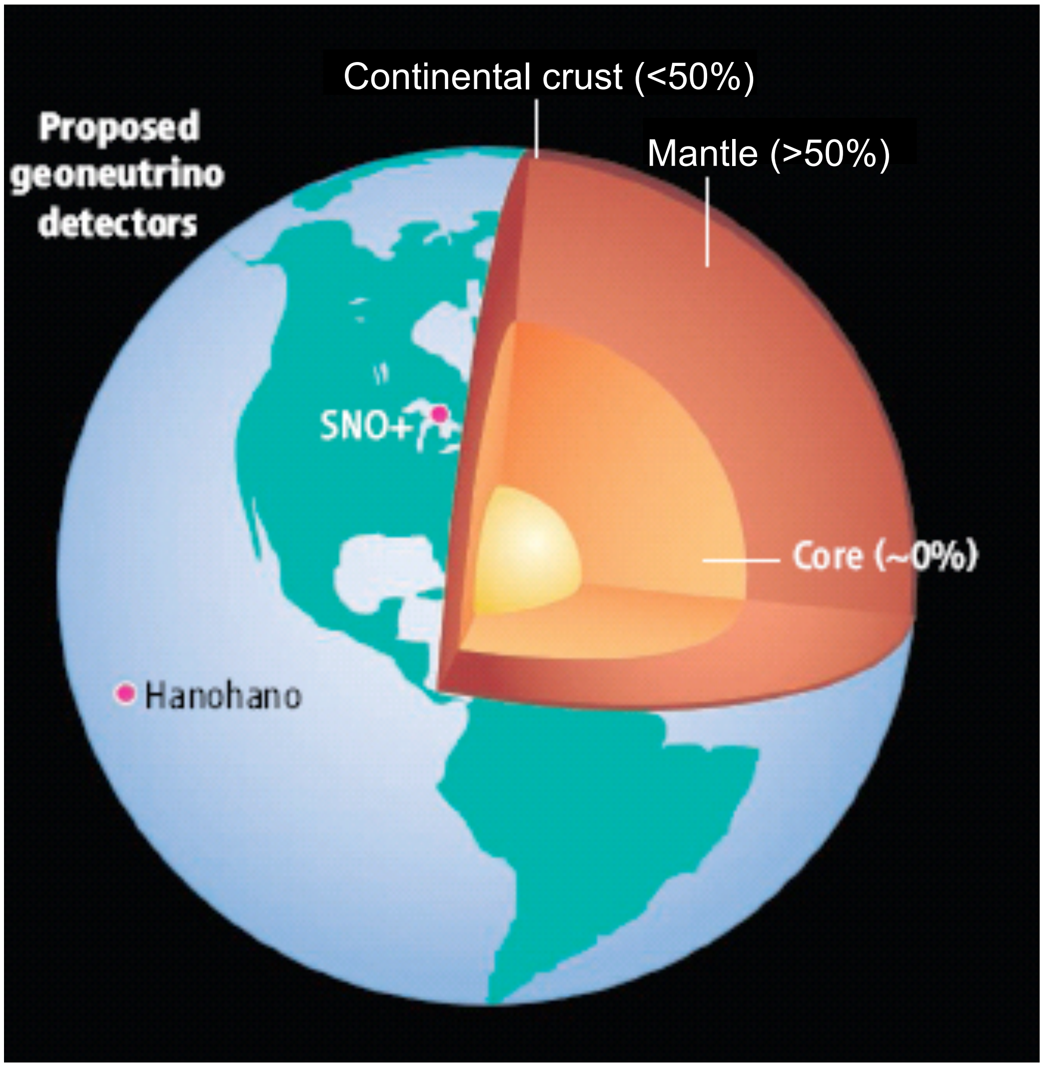
- U and Th *(K?)* are thought to be absent from the core and present in the mantle and crust.
  - Core: Fe-Ni metal alloy
  - Crust and mantle: silicates

- U and Th *(and K)* concentrations are the highest in the continental crust.
  - Continents formed by melting of the mantle.
  - K, U and Th prefer to enter the melt phase

- Continental crust: insignificant in terms of mass but major reservoir for U, Th, K.

U in the Earth:

"Differentiation"



~13 ng/g U in the Earth

Metallic sphere (core)
<<<1 ng/g U

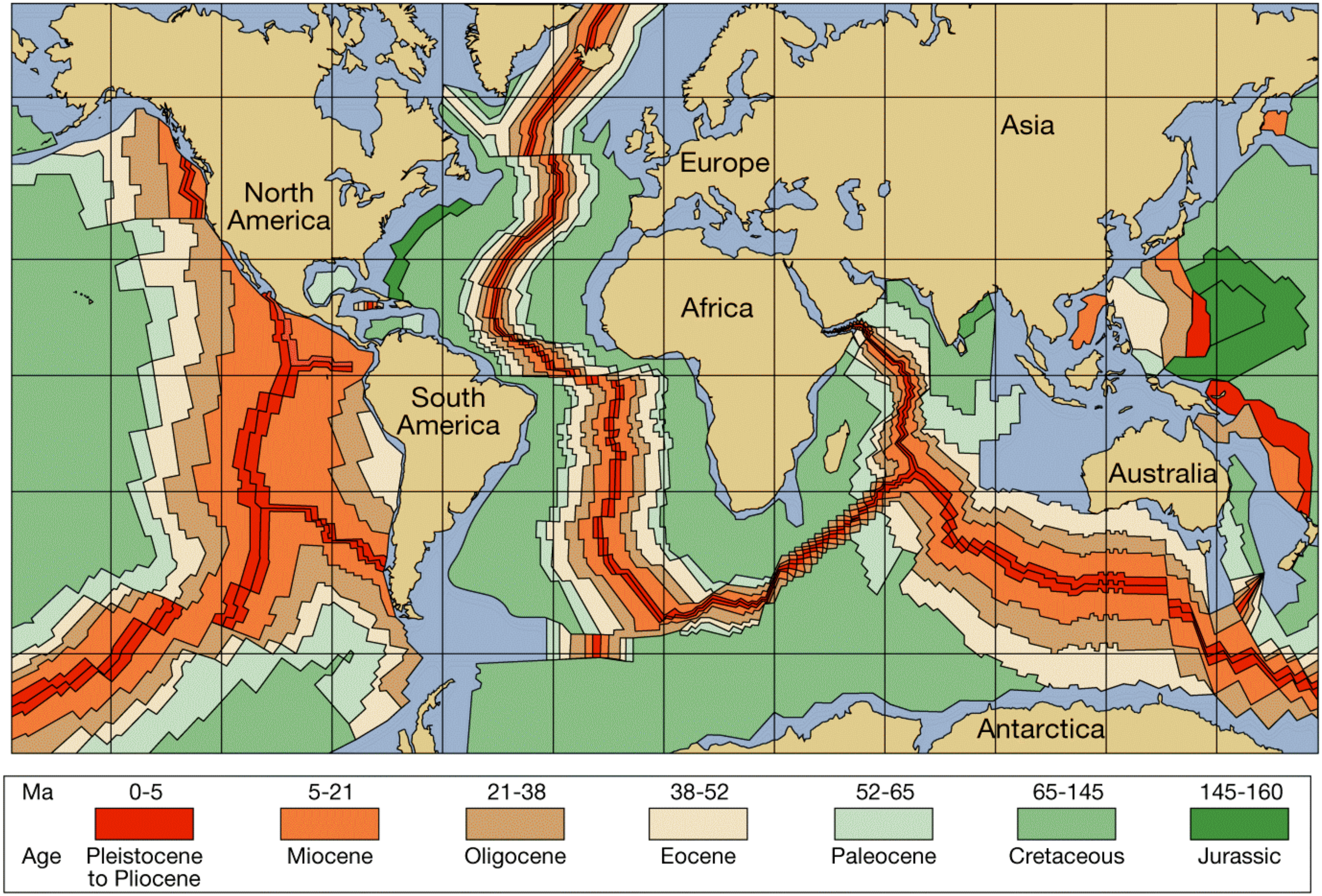
Silicate sphere
20 ng/g U

Continental Crust
1000 ng/g U

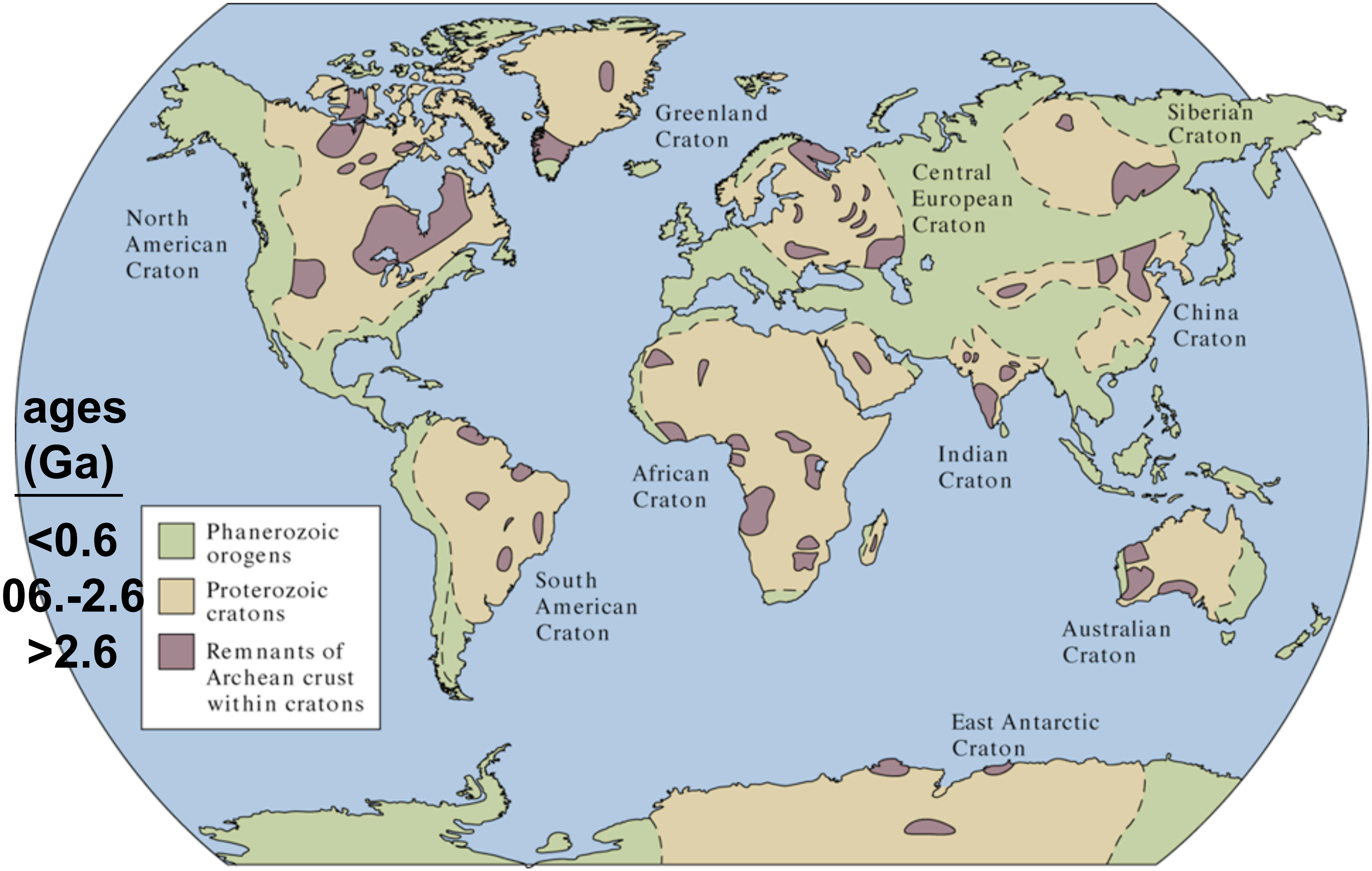
Mantle
10 ng/g U

Chromatographic separation
Mantle melting & crust formation

Oceanic crust <<200 million years old



Continents up to 3500 million years old



ages (Ga)

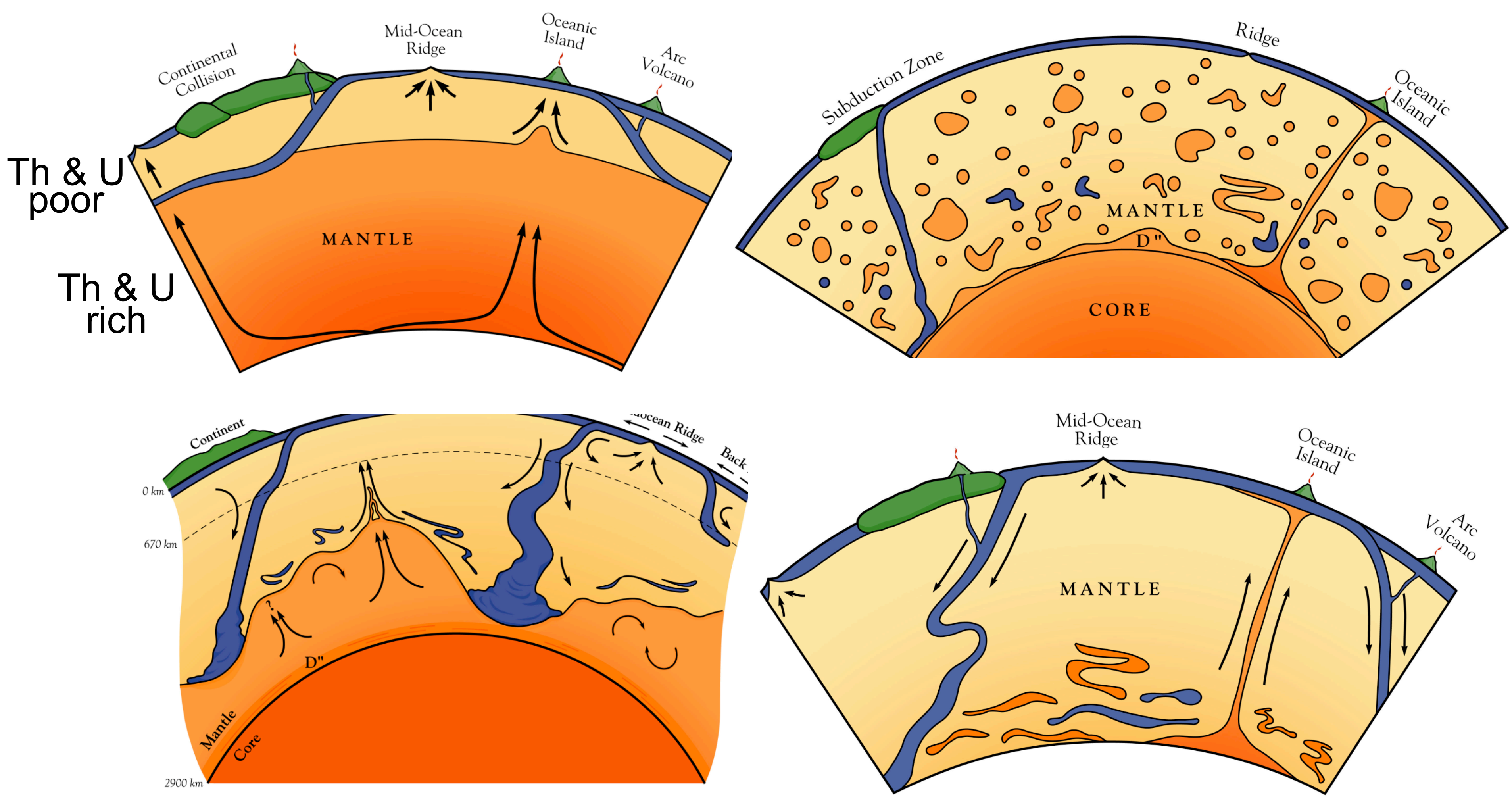
<0.6

06.-2.6

>2.6

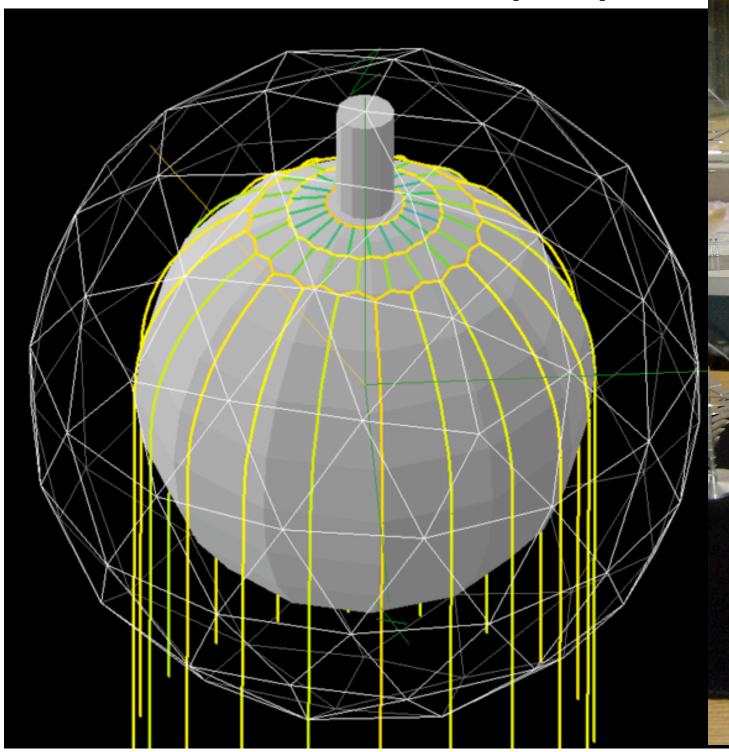
Mantle is depleted in some elements (e.g., Th & U) that are enriched in the continents.

-- models of mantle convection and element distribution



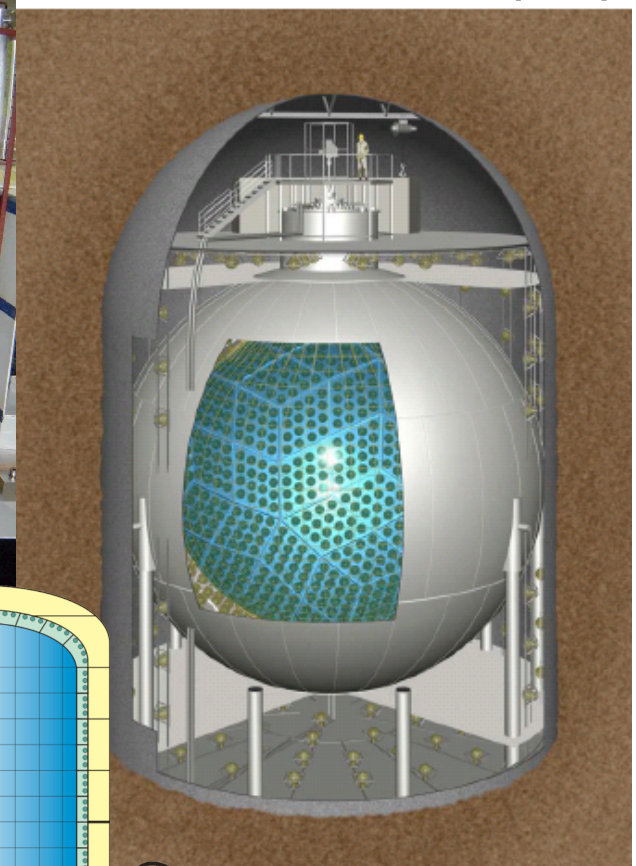
Large liquid scintillation detectors used for measuring the Earth antineutrino flux

SNO+, Canada (1kt)

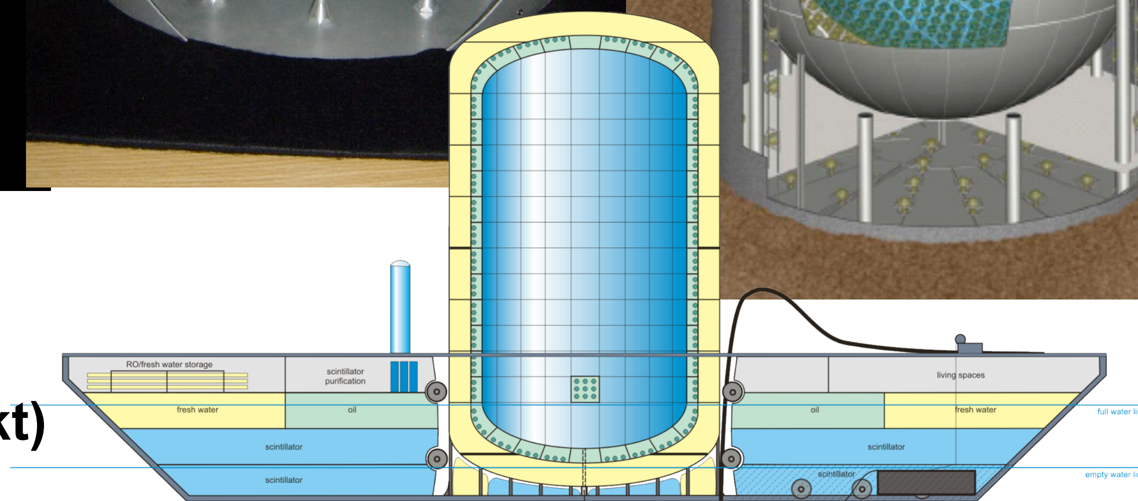


Borexino, Italy (0.6kt)

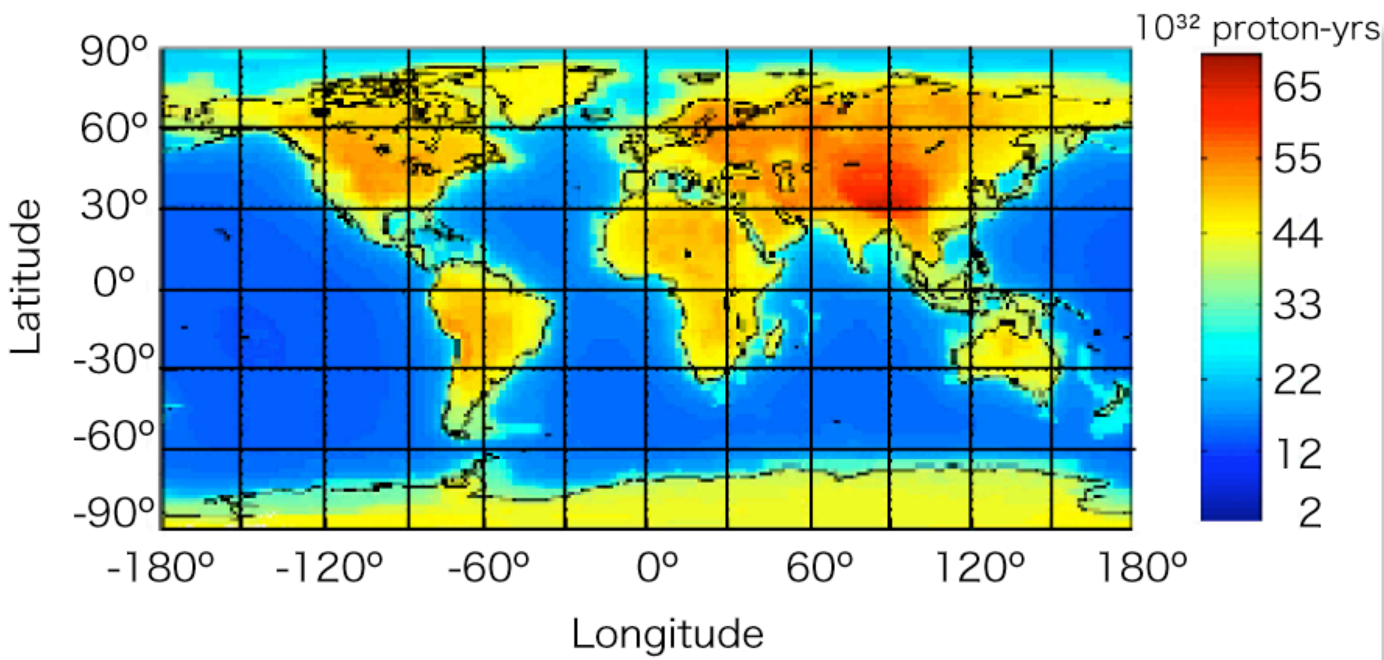
KamLAND, Japan (1kt)

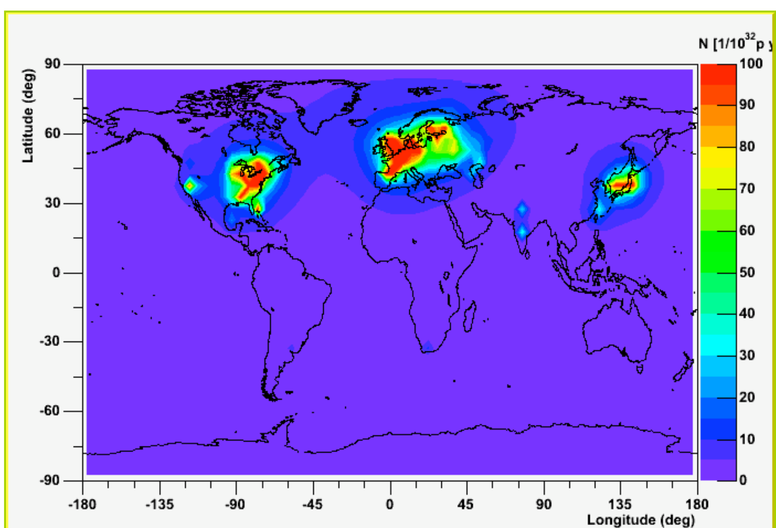


Hanohano, US ocean-based (10kt)



Predicted Geoneutrino Flux





Reactor Flux - irreducible background

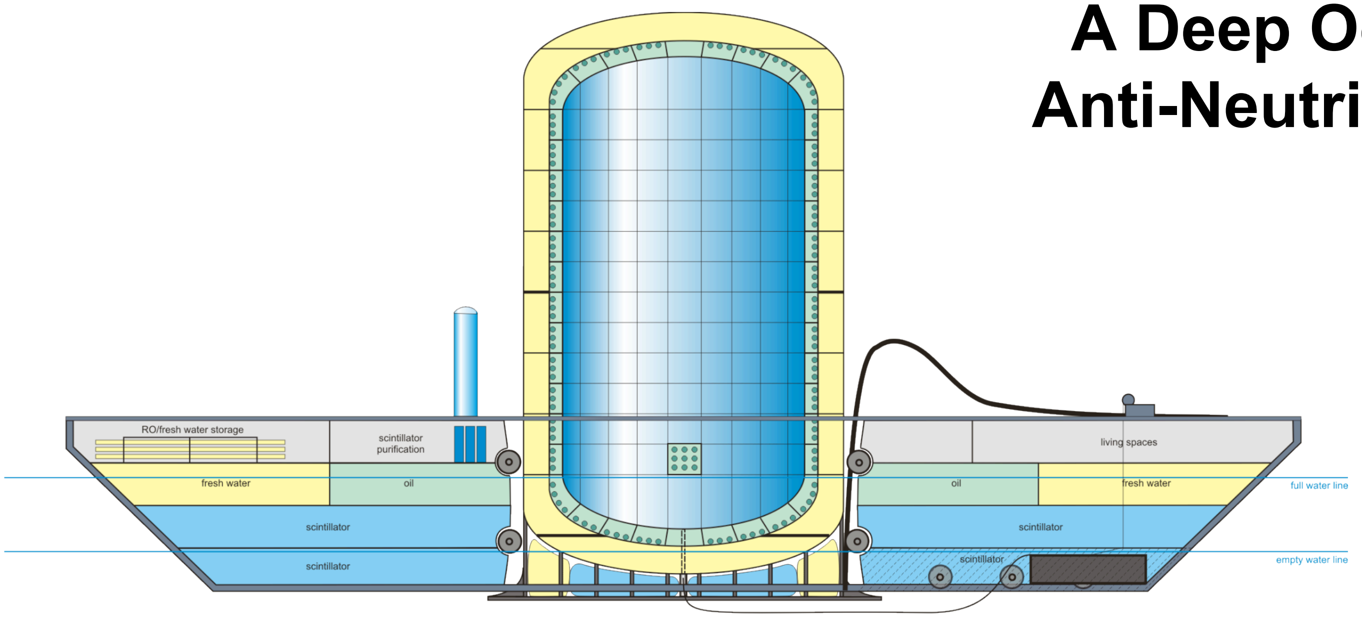
Geoneutrino flux determinations

-continental (Dusel, SNO+, LENA?)

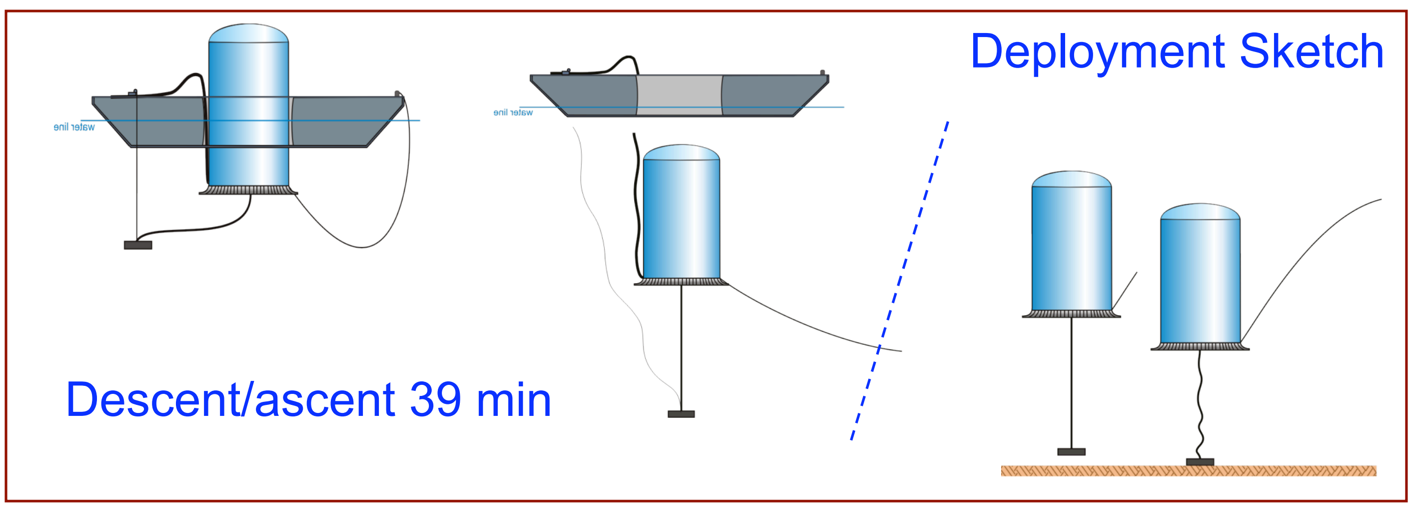
-oceanic (Hanohano)

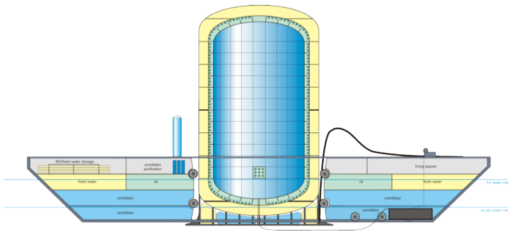
Hanohano

A Deep Ocean Electron Anti-Neutrino Observatory



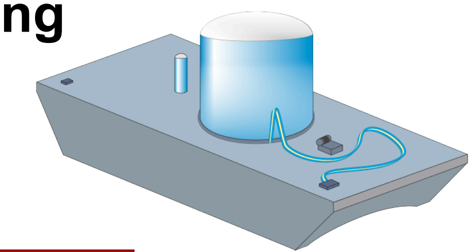
- multiple deployments
- deep water cosmic shield
- control-able L/E detection





Engineering Studies

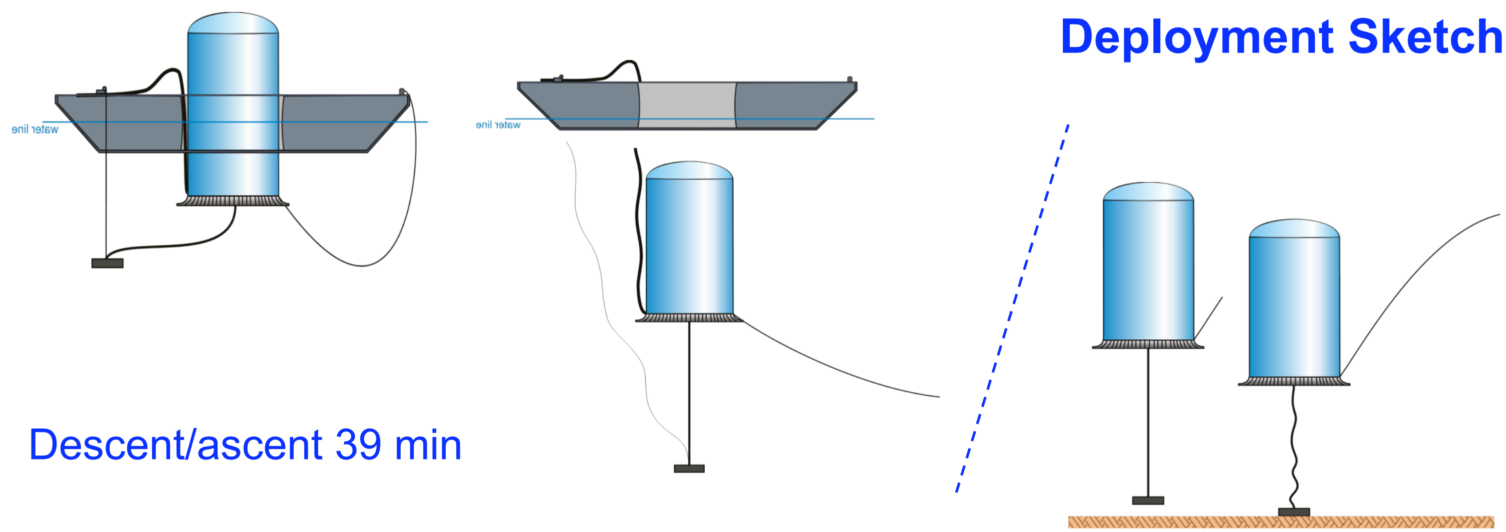
Makai Ocean Engineering



- **Studied vessel design up to 100 kilotons, based upon cost, stability, and construction ease.**
  - **Construct in shipyard**
  - **Fill/test in port**
  - **Tow to site, can traverse Panama Canal**
  - **Deploy ~4-5 km depth**
  - **Recover, repair or relocate, and redeploy**

Barge 112 m long x 23.3 wide

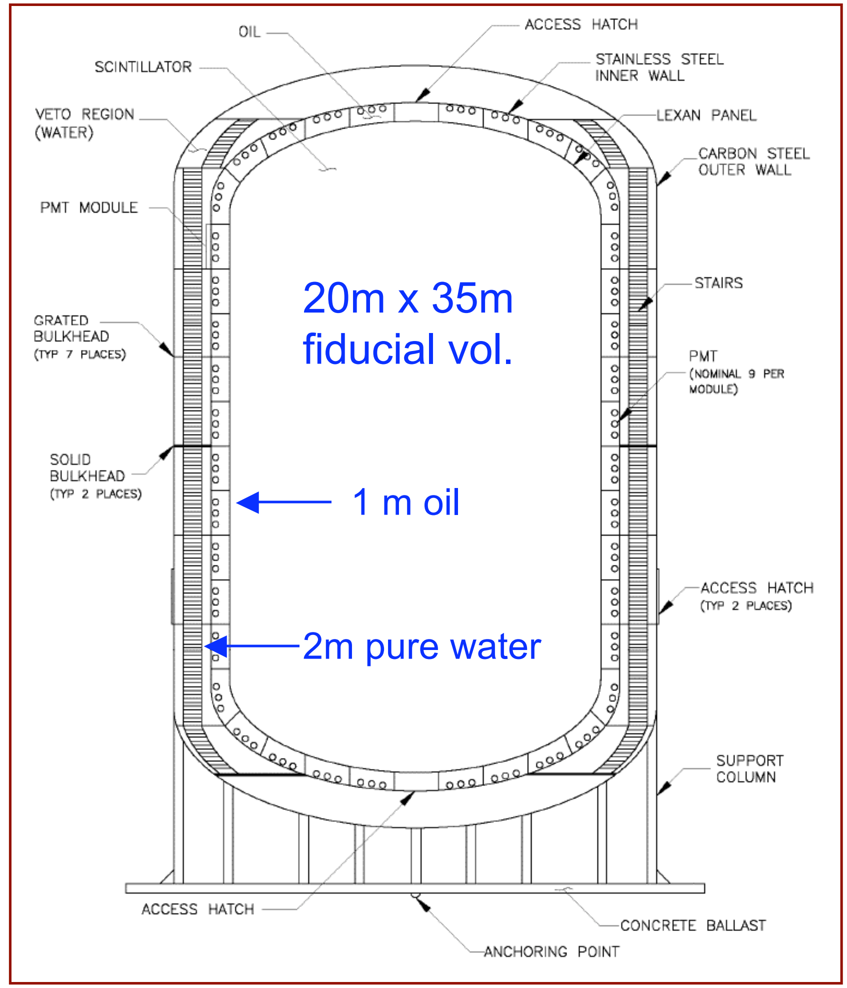
Deployment Sketch

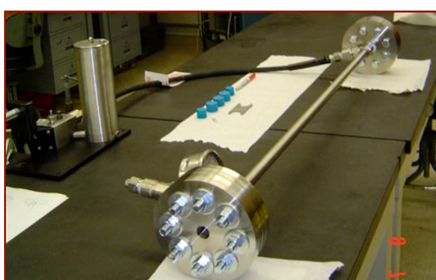


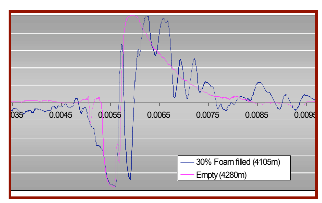
Descent/ascent 39 min

Addressing Technology Issues

- Scintillating oil studies in lab
  - P=450 atm, T=0°C
  - Testing PC, PXE, LAB and dodecane
  - No problems so far, LAB favorite… optimization needed
- Implosion studies
  - Design with energy absorption
  - Computer modeling & at sea
  - No stoppers
- Power and comm, no problems
- Optical detector, prototypes OK
- Need second round design







Summary of Expected Results
Hanohano- 10 kt-yr Exposure

- **Neutrino Geophysics- near Hawaii**
  - Mantle flux U geoneutrinos to ~10%
  - Heat flux ~15%
  - Measure Th/U ratio to ~20%
  - Rule out geo-reactor if P>0.3 TW
- **Neutrino Oscillation Physics- ~55 km from reactor**
  - Measure $\sin^2(\theta_{12})$ to few % w/ standard ½-cycle
  - Measure $\sin^2(2\theta_{13})$ down to ~0.05 w/ multi-cycle
  - Δm^2_{31} to less than 1% w/ multi-cycle
  - Mass hierarchy if $\theta_{13} \neq 0$ w/multi-cycle & no near detector; insensitive to background, systematic errors; complementary to Minos, Nova
  - Lots to measure even if θ_{13}=0
- **Much other astrophysics and nucleon decay too….**
- **And then there is the Security & Societal applications**

Paramount Request

Detecting Potassium (K) $\overline{\nu}_e$

(1) Significant for the Planetary budget of volatile element
-- What did we inherit from our accretion disk?

(2) Fundamental to unraveling Mantle structure
-- ^{40}K controls mantle Ar inventory $^{40}K \rightarrow {}^{40}Ar$ (EC)

(3) Geophysics want K in core to power the Geodynamo?
-- We don’t understand the energy source…